Mars Helicopter Telecom

IEEE Buena Ventura, Microwave Theory and Techniques Chapter Meeting, July 19, 2018

Courtney Duncan, Jet Propulsion Laboratory, California Institute of Technology

Notices & Disclaimers

- © 2018 California Institute of Technology, Government sponsorship acknowledged

- The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

- Reference herein to any specific commercial product, process, or service b trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

Mars Helicopter Telecom JPL Team

- Scot Stride – Hardware, Testbed
- Nacer Chahat – Antennas
- Lauren McNally - Radio Software
- Matt Chase – Interface Software
- Charles Wang / Anusha Yarlagadda - Testbed
- Carl Spurgers – Electronics Design Advisor
- Peter Ilott – M2020 Telecom
- Courtney Duncan – MH Telecom Lead
- Eric Archer - Founder

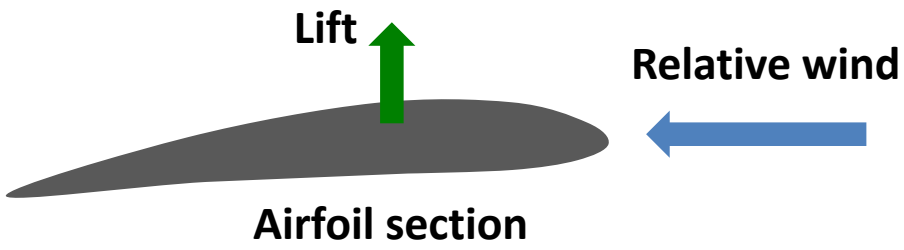
What is a Helicopter?

- An Aerial Vehicle that can hover

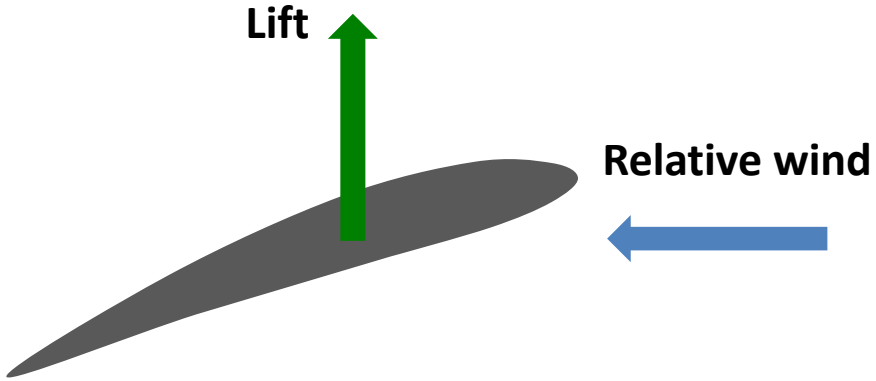
- Interesting Control Features
  - Blades operate at constant RPM throughout flight
  - Controlled by “Collective” and “Cyclic” pitch on blades
  - Via swashplate from servos (or “stick and rudder” for human pilots)

- Mars Helicopter is a two-rotor counter-rotating design
  - Eliminates need for pesky tail rotor yaw control

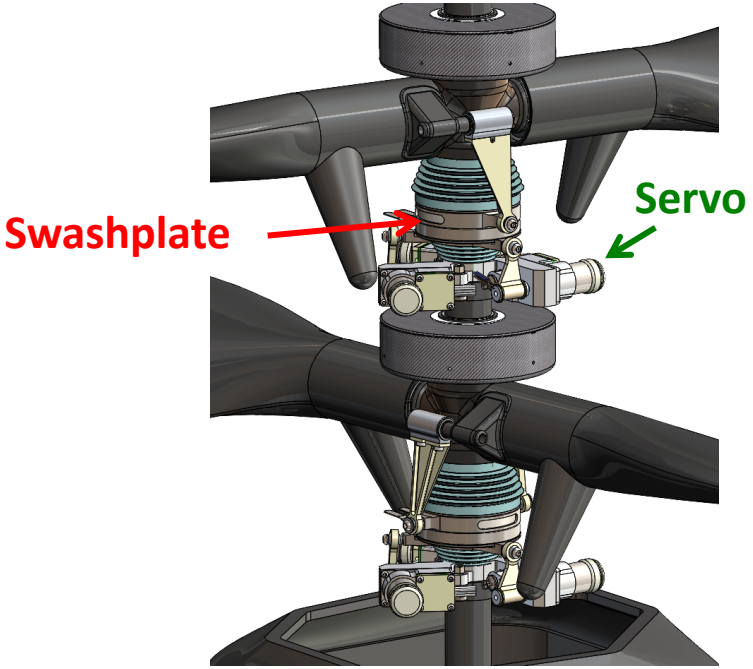
Helicopter is Controlled with Variable Pitch



Increased pitch ⟶ Increased lift



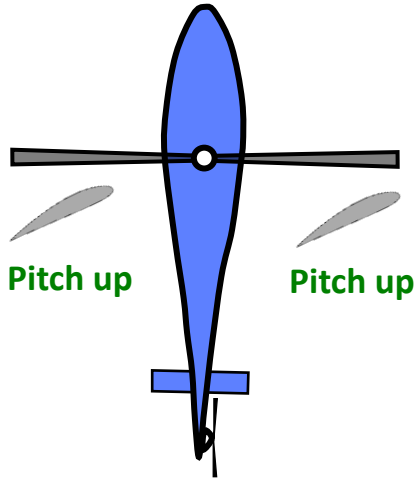
Pitch controlled with servos that move *swashplates*



Types of Pitch Variation

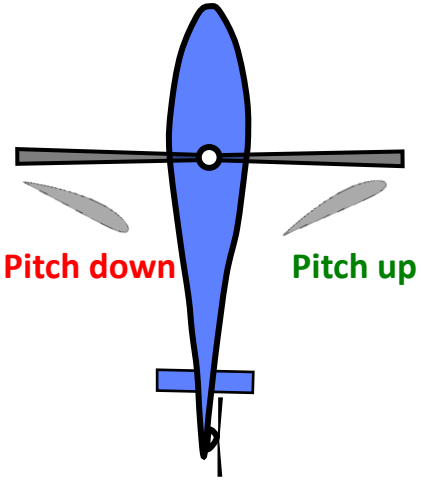
Collective control

- Changes *average* blade pitch



Cyclic control

- Changes blade pitch *periodically*
- Increases lift on one side
- Decreases lift on other side



What is Mars Helicopter?

- First Aerial Vehicle intended to fly on another planet
- Class D Technology Demonstration
- Planned for deployment on Mars by the Mars 2020 Rover
  - Launches July 2020
  - Arrives February 2021

- Major Challenges
  - Air is thin: 8 torr (30 km Earth atmosphere equivalent) CO_2
  - Must fit into some ~meter sized M2020 carrying envelope
  - So: Mass < 1.8 kg
  - Also: Environment is cold: < -40 C, at night < -100 C
  - Power very tight: 20 W-h battery, solar panel, survival heaters
    - Sorties (@~400 W) are 90-seconds on four-sol cadence

Why Demonstrate A Planetary Helicopter?

- “Fetchers” and “Explorers”
- Fetchers go carry something from one place to another
  - Like collected rock samples to a single pile for Mars Sample Return
- Explorers go places that Rovers can’t go
  - Or scout ahead multiple places rovers might consider going

- “Real” Helicopters could be much larger, “their own mission”
  - Like a quad copter with blades like this one
- The “Real” Helicopters could be on the Mars Network
  - Not leashed to a rover by a short range radio

- (This is all speculation today)

AeroVironment – Major Industrial Partner

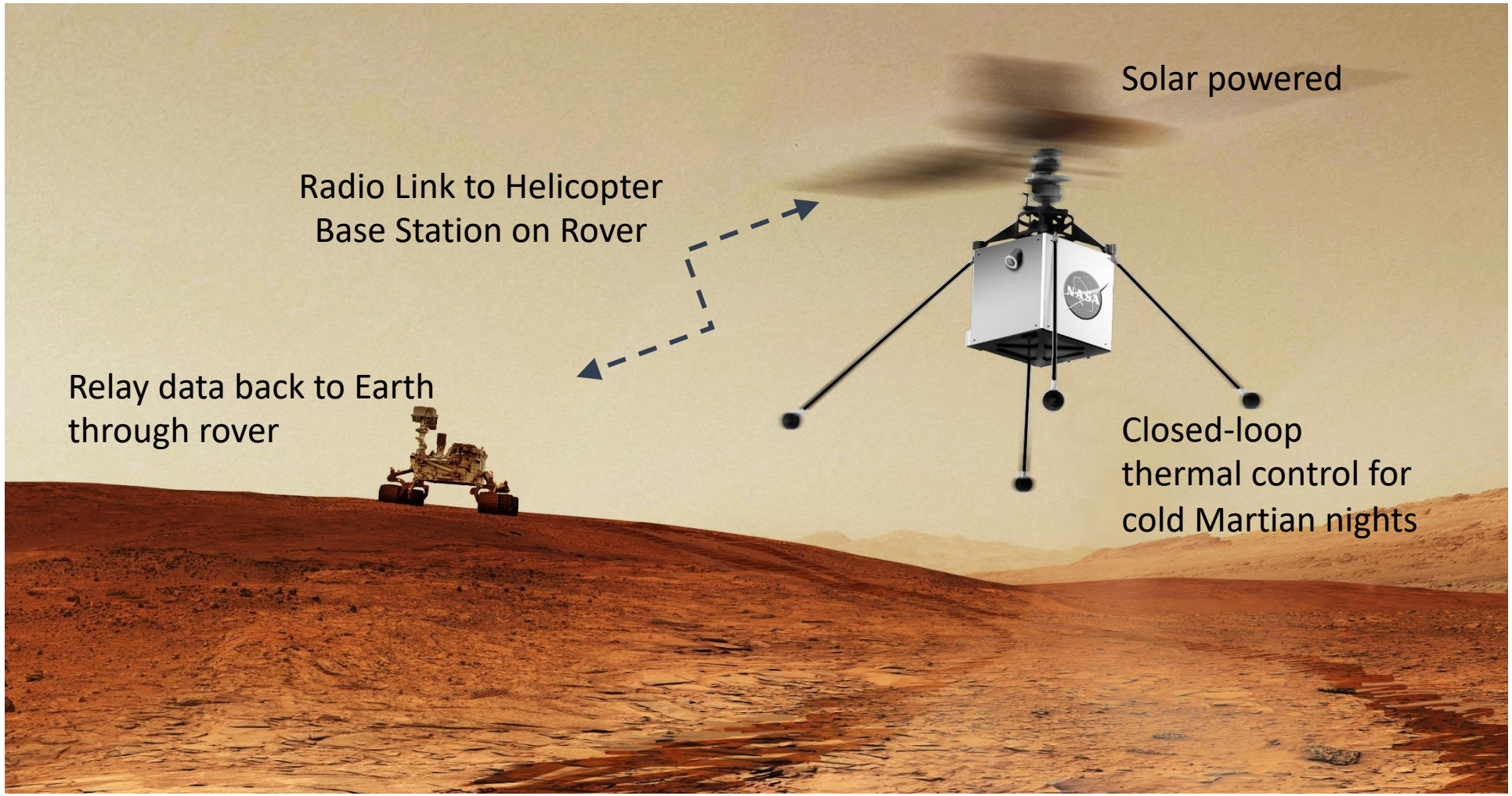
- Founded by Paul MacReady
  - Designer of the human-powered Gossamer Condor that won the Kremer Prize
  - And the Gossamer Albatross that crossed the English Channel
    - Piloted by Bryan Allen, now at JPL
- Simi Valley, CA
- Unmanned, electric aerial vehicles, drones and such
- Experience with unusual designs and environments
- Military systems, precision agriculture, etc.

- Mars Helicopter rotors, motors, servos, mast & wiring, landing gear
  - JPL does the rest – electronics, IP, I&T, ATLO

Mars Helicopter Technology Demonstration on Mars 2020

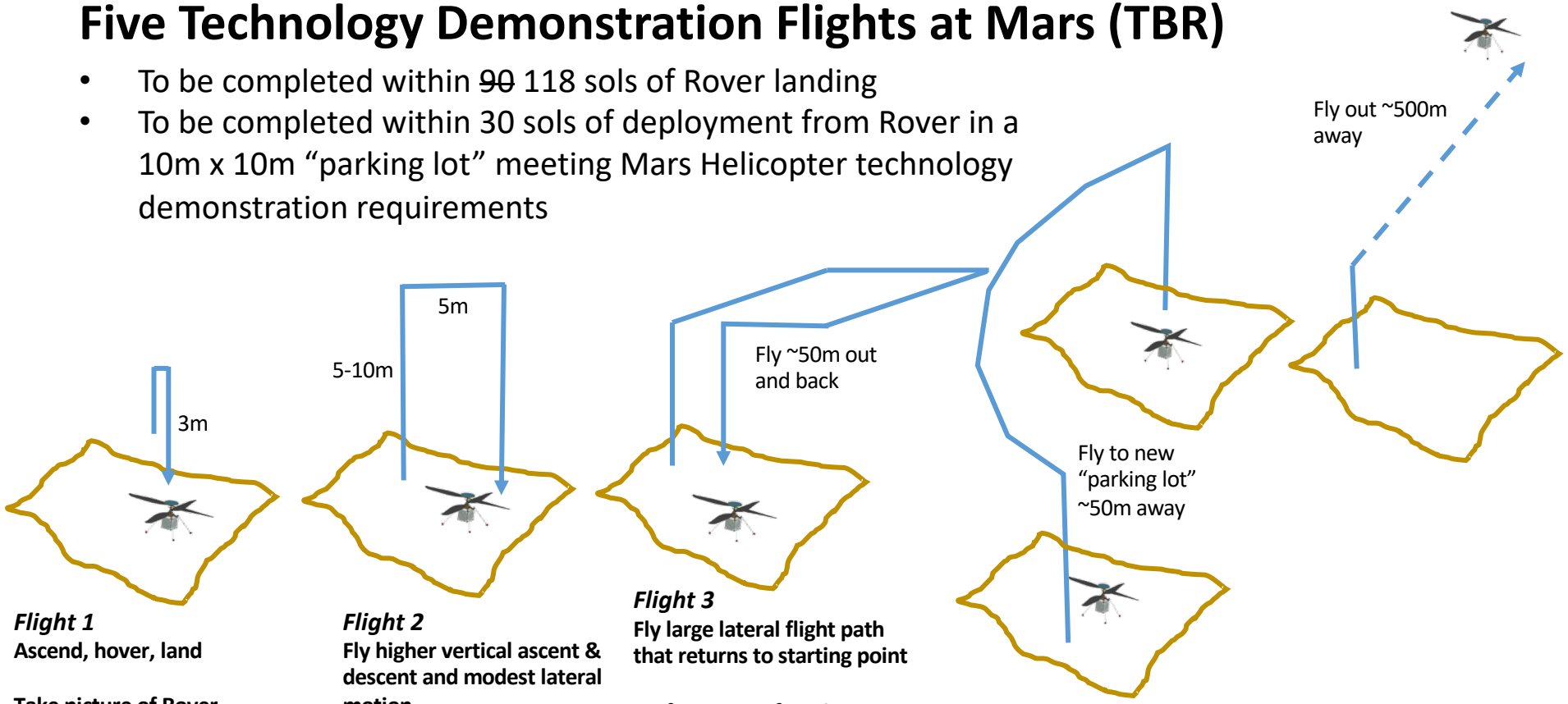
- Capable of flight in thin Mars atmosphere (~1% of Earth)
- “Co-axial” Helicopter
- Blades 1.2-meter tip-to-tip
- Mass ~1.8 Kg
- Solar powered – up to 90-second flight per sol
- Flight distances up to 300 m
- Heights up to 10 m
- Autonomous flight & landing
- Up to 5 flights
- Telecommunication to Base Station on Rover
- Self-sufficient thermal control

After Deployment from Rover *(cutting of the UART)*, Mars Helicopter Operates in Stand-Alone Fashion, with Radio Link to Base Station on Rover



Five Technology Demonstration Flights at Mars (TBR)

- To be completed within ~~90~~ 118 sols of Rover landing
- To be completed within 30 sols of deployment from Rover in a 10m x 10m "parking lot" meeting Mars Helicopter technology demonstration requirements



Flight 1
Ascend, hover, land

Take picture of Rover

Rover takes picture of Helicopter in flight

Minimum Mission Success

Flight 2
Fly higher vertical ascent & descent and modest lateral motion

Flight 3
Fly large lateral flight path that returns to starting point

Perform scout function to image terrain far ahead of "parking lot"

Certify new "parking lot" (on Earth)

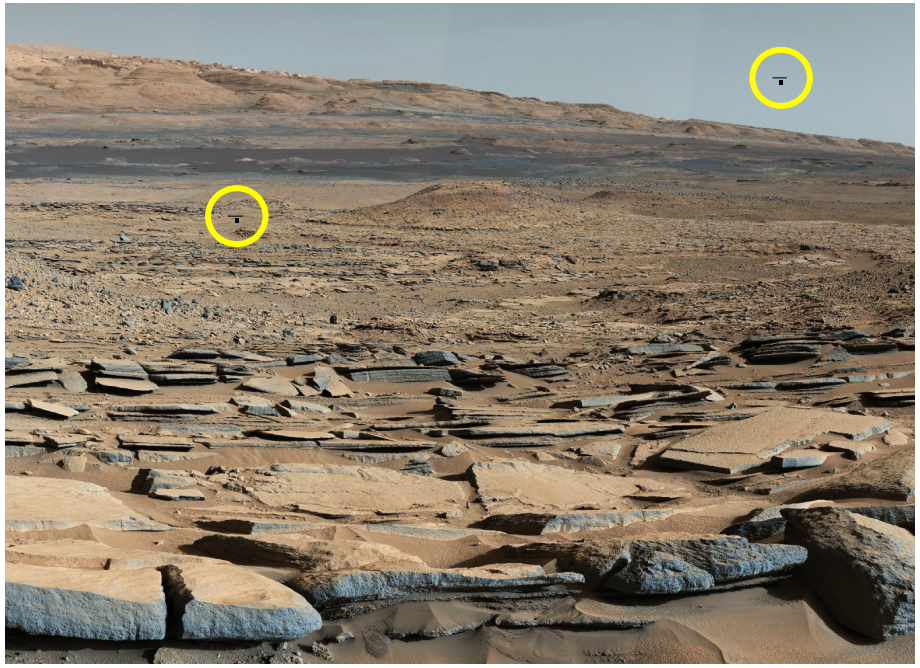
Flight 4-5
Contingency for Flights 1-3

If contingency flights are not needed, then consider the following options:

Fly to new "parking lot"

Fly away to maximum distance that the vehicle can fly (~500m). Note: destination landing site will not have been surveyed.

Potential Images From Rover



- NavCams at 100m:< 3.5 cm/pixel

- At highest resolution:
  - Blade length = 36/5120 pixels
  - Body cube = 3.6/5120 pixels

- NavCam Imaging Plan Proposal:
  - 2x2 & 2x2 tile exposed and read out every ~ 6 seconds
  - 7 cm/pixel

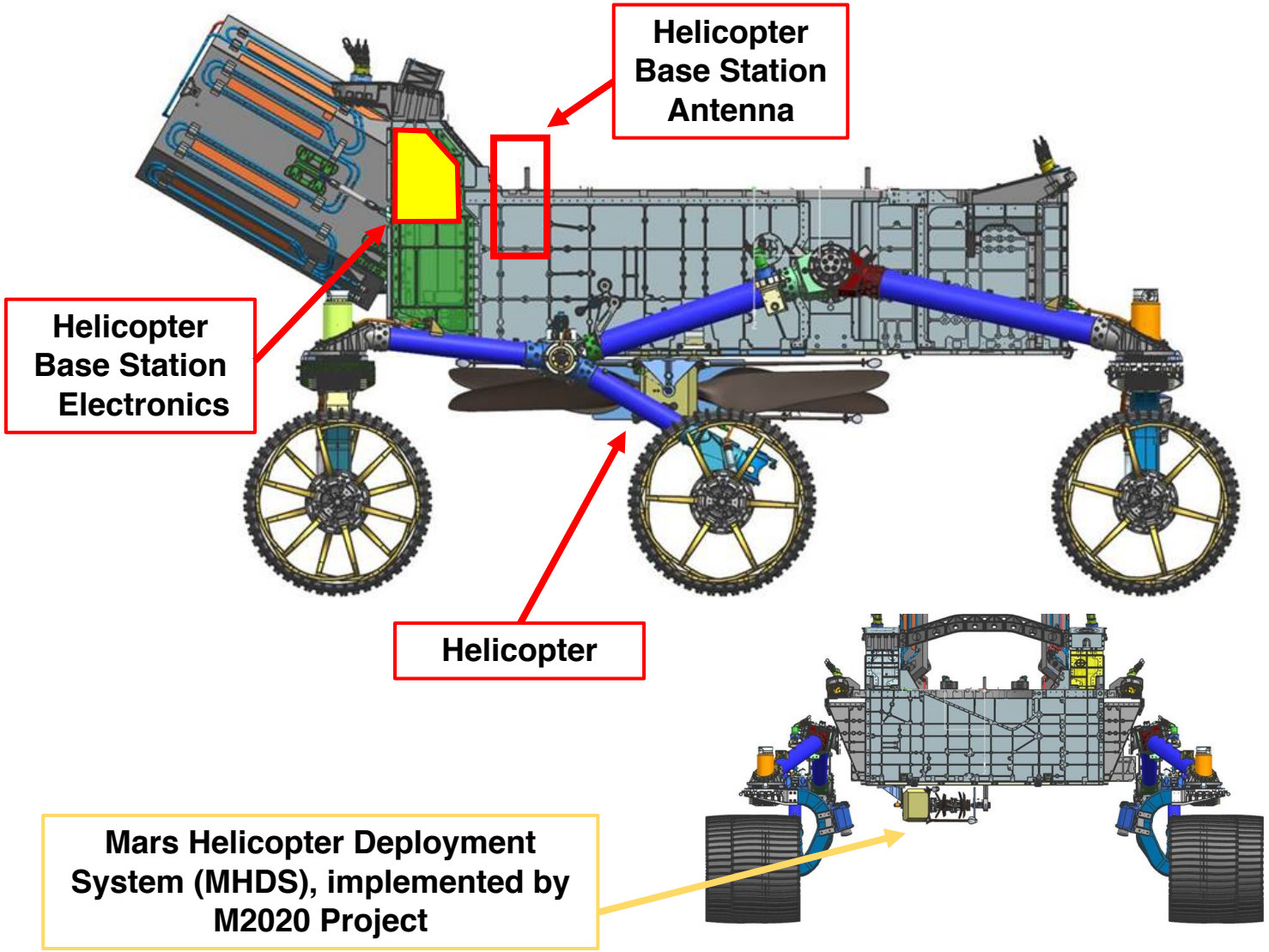
Mastcam-Z
(Full Res) w/ some noise)

Blades are ~ 145 pixels at full zoom
Body Cube ~ 19 pixels at full zoom

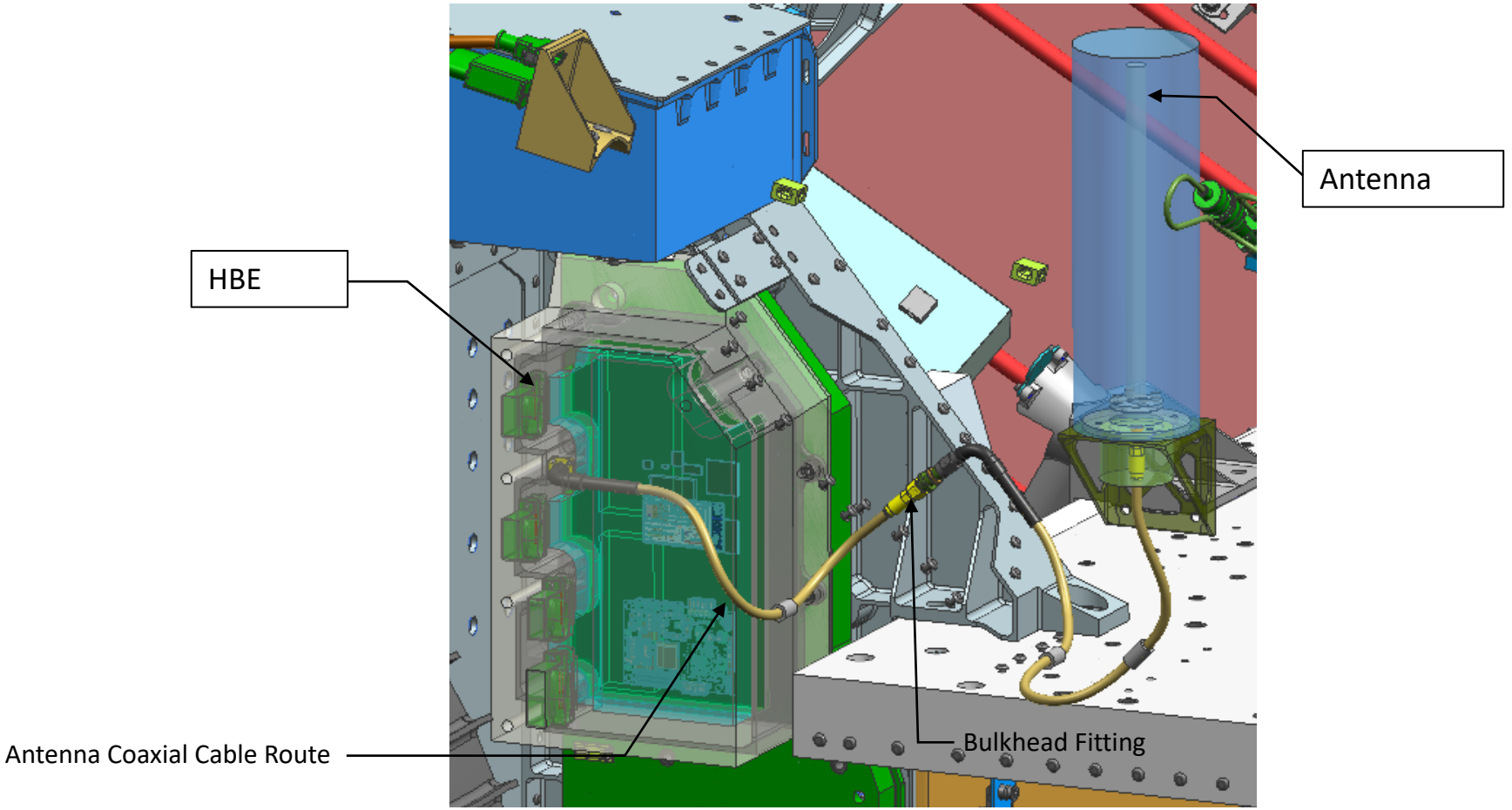
FM Baseline Design

1.2 m blade span
Counter-rotating
1.8 kg max mass
Solar power
Autonomous
Radio "leash" to M2020 Rover

Mars Helicopter Accommodation on Mars 2020 Rover



Helicopter Base Station (HBS), Antenna (HBA) and Coax detail



“Leonardo” Mission Status

- Passed “ready for flight build” review 12/18/17 – 12/19/17
- Free Flight Hover in 10’ chamber (B150) 1/9/18 19:30 local – Key Gate
  - 8 torr
  - Gravity offload to get to 0.38 G Mars
  - Video later
- “Flight Build Workshop 1/26/18, 1/29/18
  - One FM to be built with spare parts set
- Approved by NASA HQ for manifest on Mars 2020 Rover, 5/11/18

- We want to call it “Leonardo” (for da Vinci) but ultimate funder has naming rights

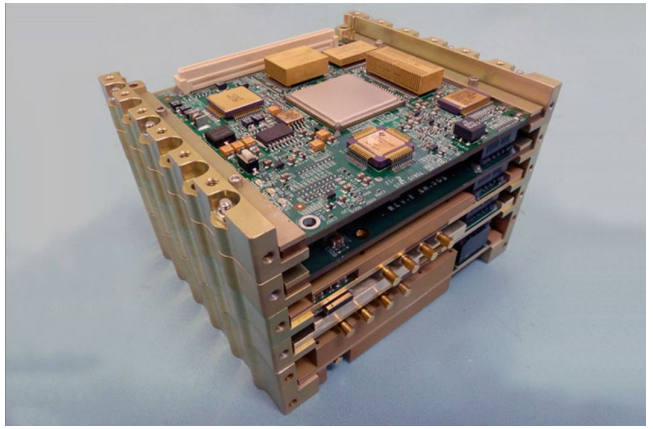
Telecom “Objectives”
(no “Requirements” on MH)

- 10 gram mass
  - Includes antennas and cables
  - 13.3 grams achieved (helicopter side)
- Rover side uses the same electronics boards
- Telecom up to 1000 m., two-way (NFZ is 100 m. radius) (no radio-navigation)
  - OTA rates 20 kbps, 250 kbps
- DC power: TX < 3 W, RX < 0.2 W
- Temperature -40 to +85 C, -50 C non-op
- Protocol modified from ZigBee (IEEE 802.15.4)

- COTS Part Selection Criteria
  - Very Low Mass suggests COTS ISM
  - Low frequency for lowest omni to omni path loss, 900 MHz is lowest ISM band
  - “High Power” – most ISM parts run a few 10s of mW, want closer to a watt
  - Diversity – possibility of > 1 antenna

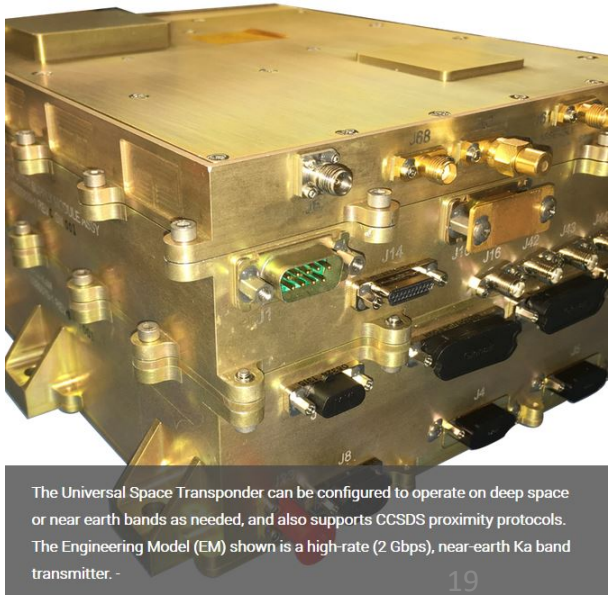
Radios that were ruled out (early)

- Iris is about the mass of the ECM (400 g.) and larger (10 cm cube vs. 7 cm cube)



- Electra on M2020 was considered for base
  - Software modification for completely new mode would take too long
  - But would have enabled much greater “tether” range

Electra UHF transponders are used to communicate between orbiters and landers at Mars. -



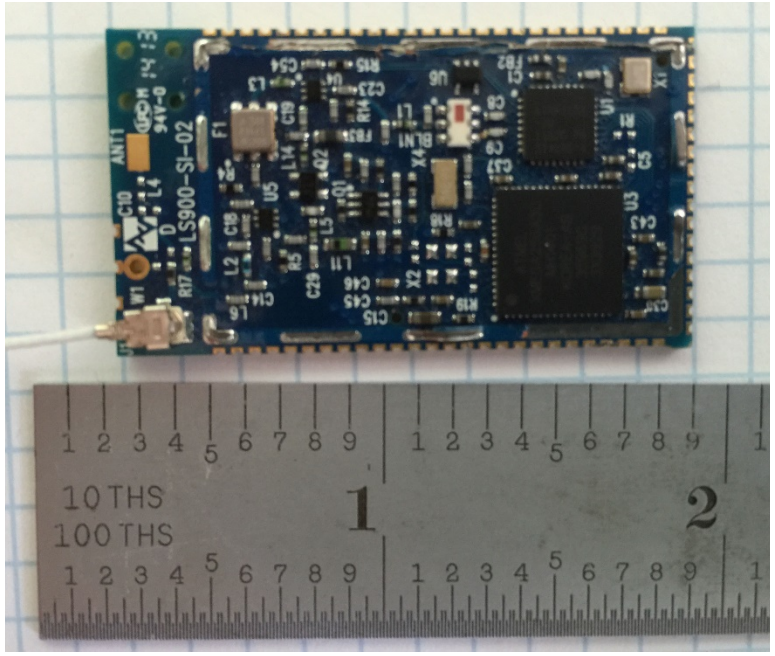
The Universal Space Transponder can be configured to operate on deep space or near earth bands as needed, and also supports CCSDS proximity protocols. The Engineering Model (EM) shown is a high-rate (2 Gbps), near-earth Ka band transmitter. -

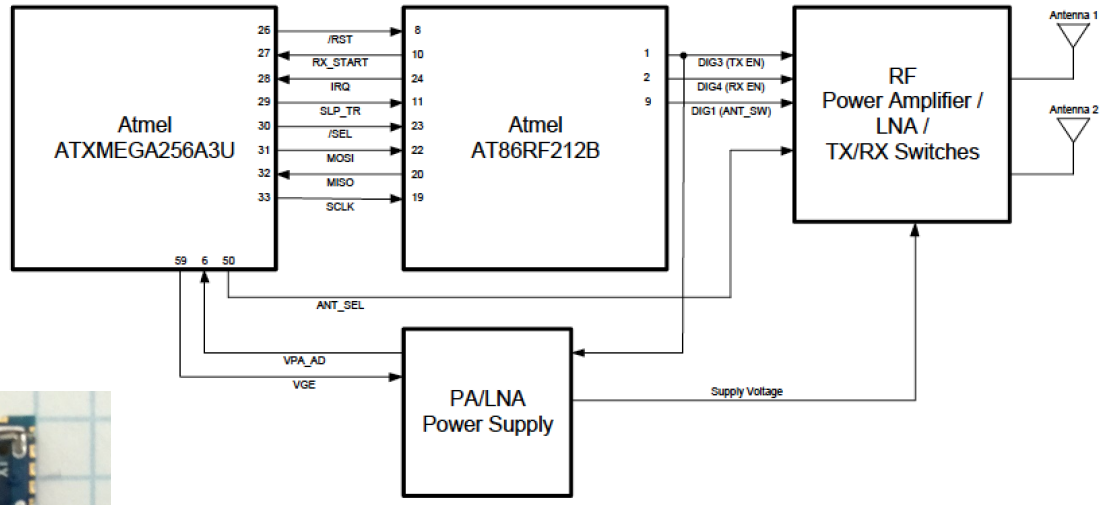
- Can’t develop a 4 gram UST on a Class D budget

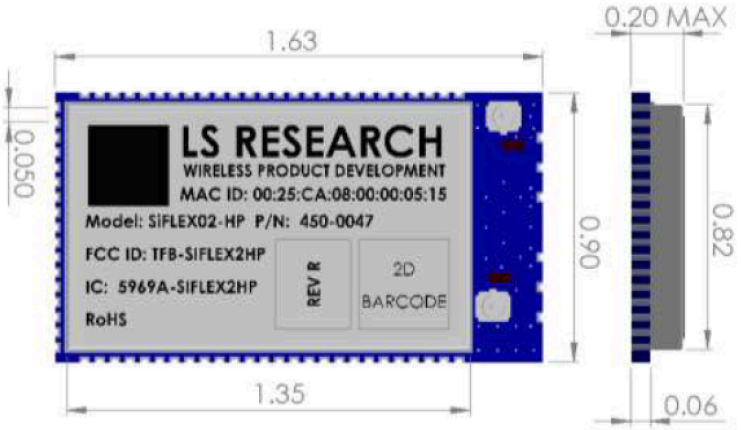
Radio that was Picked: RF Modem: LS Research SiFlex02-R2-HP

Minimum Order Qty: 50 units
Cost: $60 per unit
Mass prepped: ~3.5g
Power Out: 28 dBm
Band: 906-924 MHz (10 ch.)
Antennas: 1 or 2

… but, shortly after purchase
SiFlex sold to Laird late 2016
SiFlex support discontinued

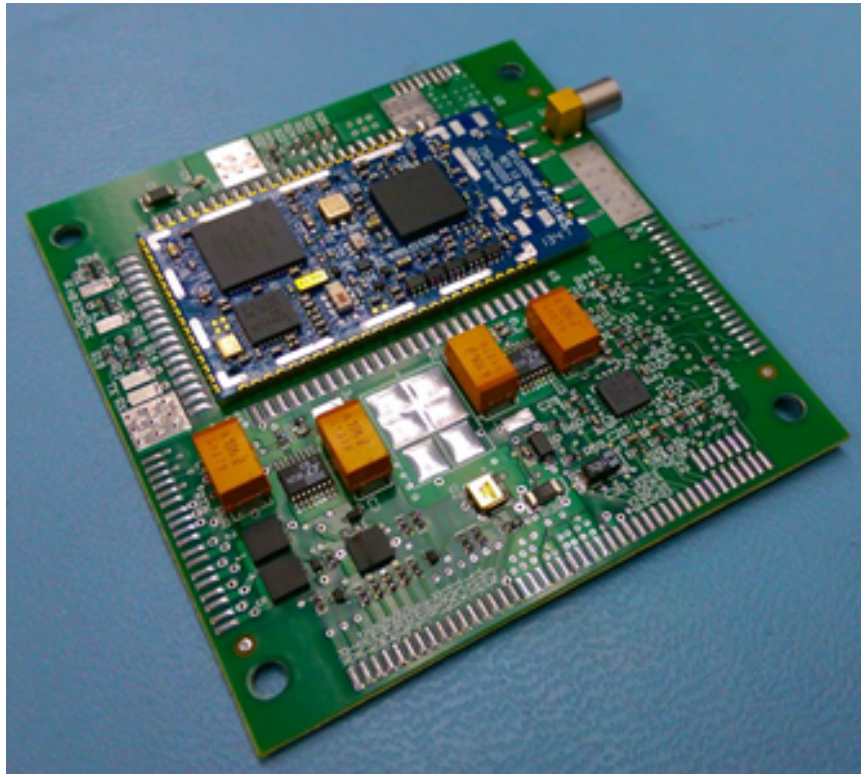




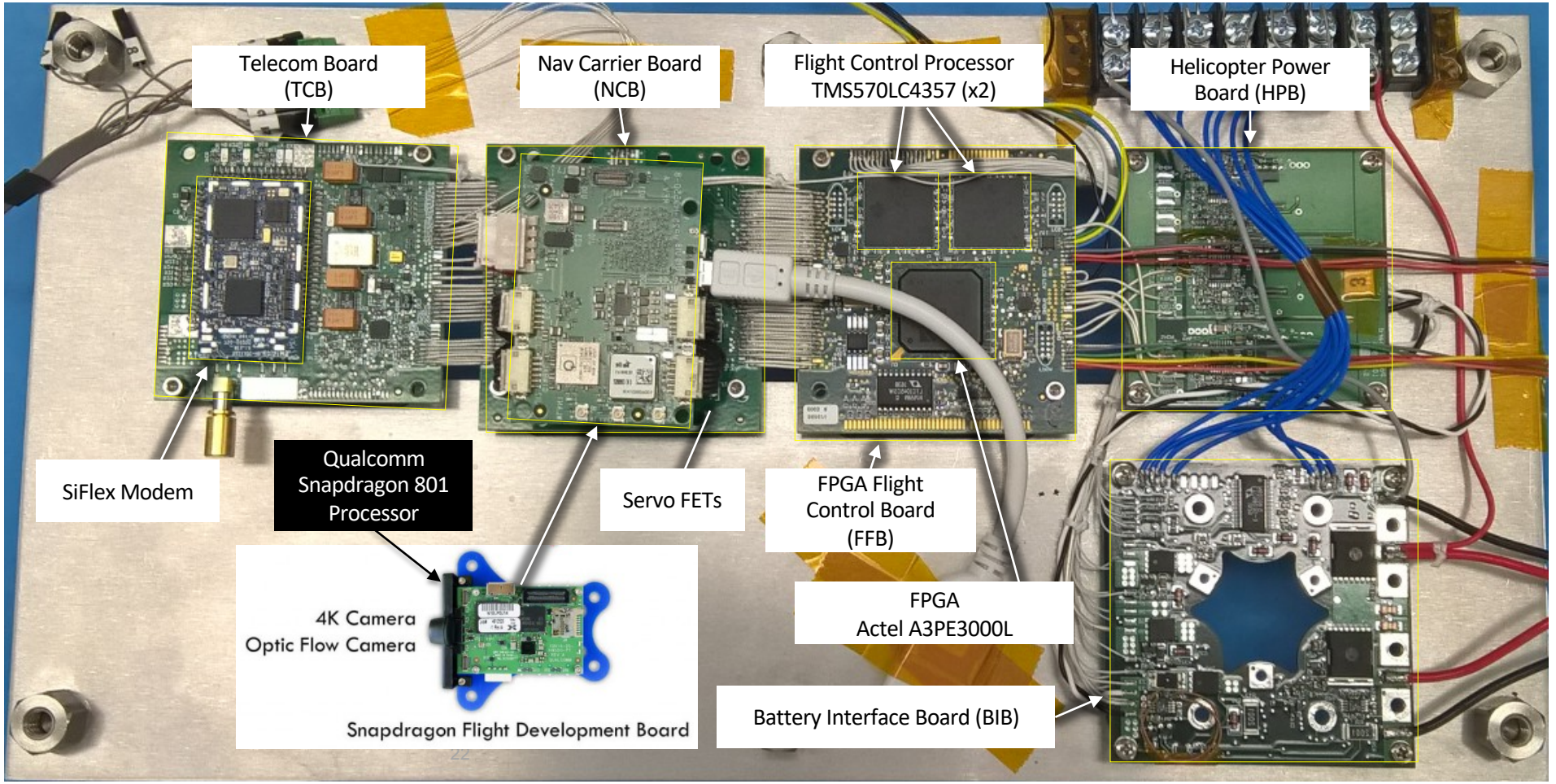


MH Telecom Board (TCB)

- Telecom Board
  - Hosts COTS SiFlex radio module
    - LSR SiFLEX02 high performance 900MHz IEEE 802.15.4 radio
    - Main radio link between helicopter and base station.
    - Identical modems on each end of the link
  - Provides 1 ADC, temperature MUX and heater control
- Both Helicopter and Base
  - Helicopter stack form factor is “cube”
  - Base stack form factor is “wallet”
- Modified SiFlex
  - Delidded – inspected – parts changes

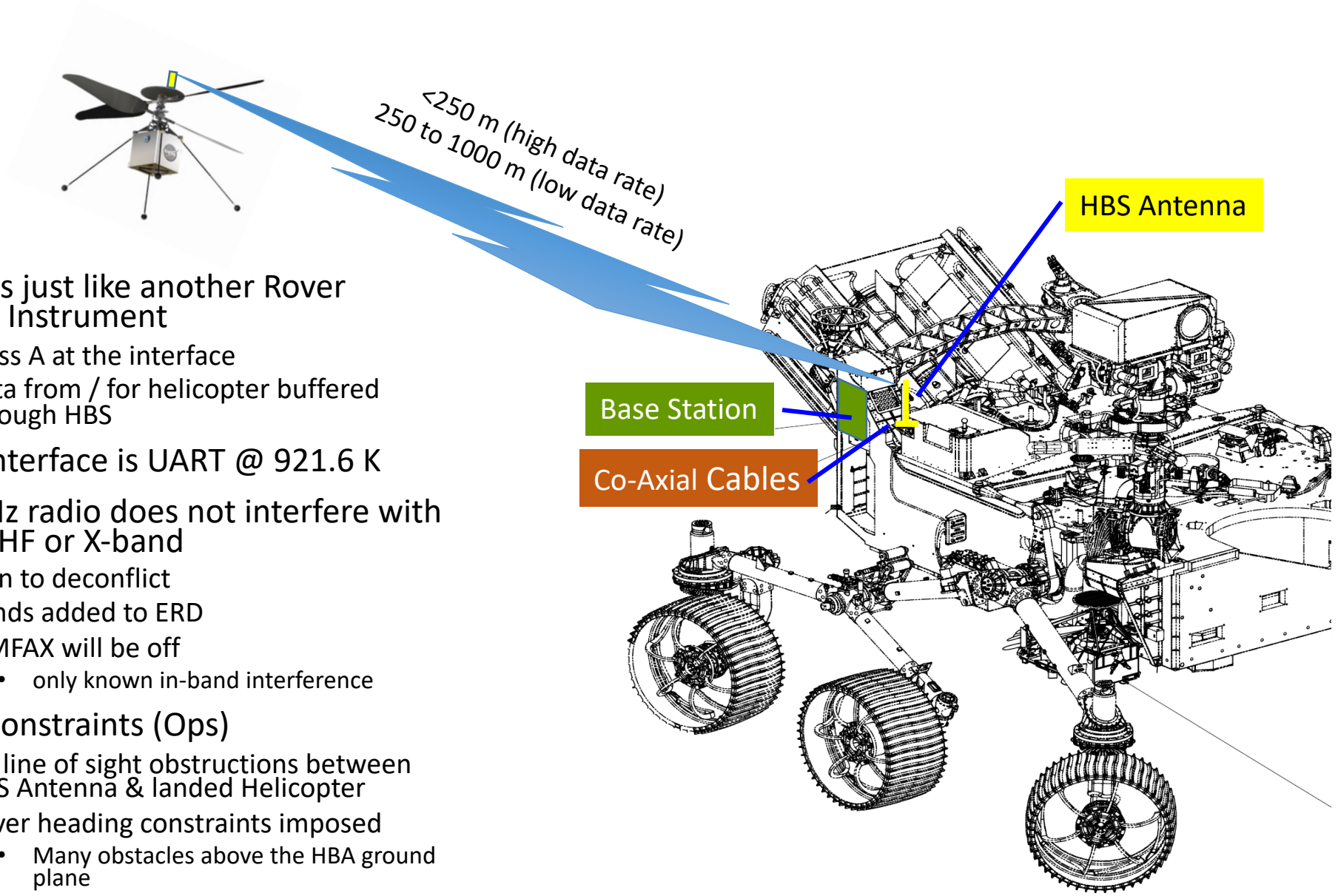


Helicopter FlatSat
Electronics Core Module (ECM)



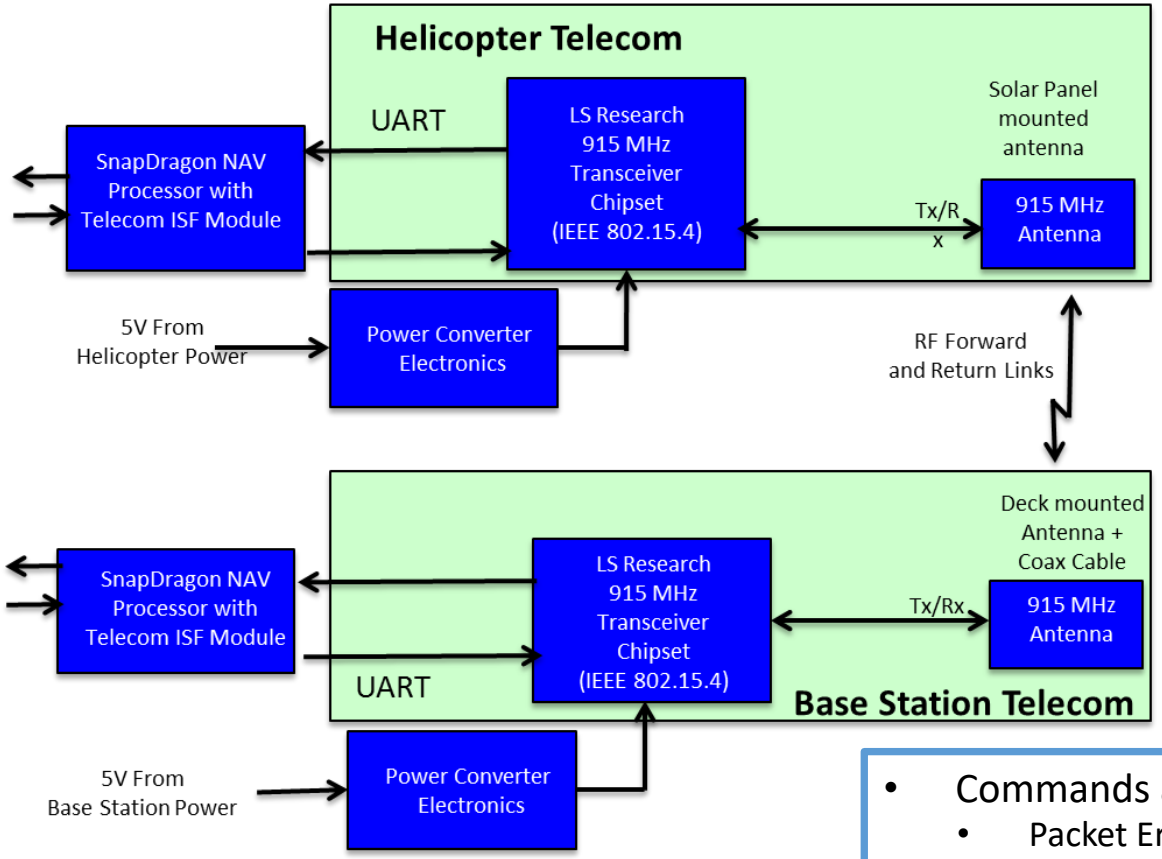
MHS Flatsat 001

Telecom Interfaces



- HBS acts just like another Rover Science Instrument
  - Class A at the interface
  - Data from / for helicopter buffered through HBS
- Radio interface is UART @ 921.6 K
- 914 MHz radio does not interfere with rover UHF or X-band
  - Plan to deconflict
  - Bands added to ERD
  - RIMFAX will be off
    - only known in-band interference
- Rover Constraints (Ops)
  - No line of sight obstructions between HBS Antenna & landed Helicopter
  - Rover heading constraints imposed
    - Many obstacles above the HBA ground plane

Telecom Design Overview



- Operation while landed or in flight
  - Range: 2 m. to 1000 m.
  - 900 MHz – low path loss

- Mass, Power, Environment
  - 13.3 g on helicopter
  - 3 W DC transmit peak
  - < 0.5 W receive
  - -40C to +60C

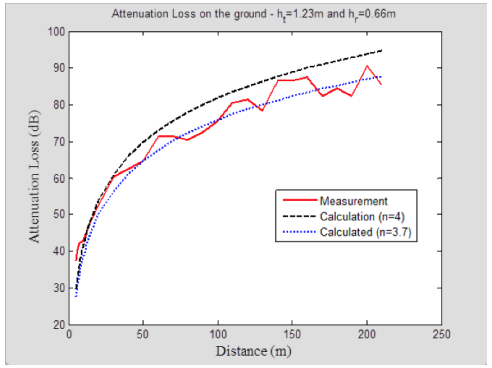
- 900 MHz activity added to ERD and license
- Part modified for full power output, touched up

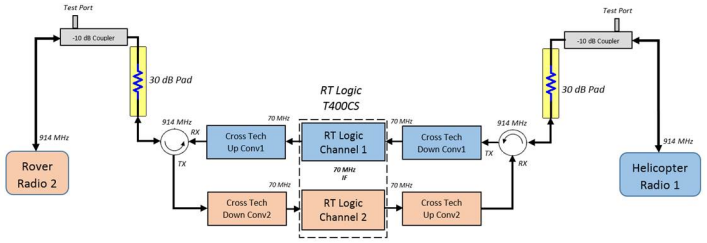
- Commands and Telemetry - 802.15.4 (ZigBee)
  - Packet Error Rate (PER) <1%
  - Packet or ack loss triggers retries, failure indication
  - Protocol adapted to two-point, high-throughput need
- Flight Software Driver – ISF
  - Heli and HBS drivers identical

Telecom Performance Tests

- Testbed verification of
  - ✓ Power output
  - ✓ Receive sensitivity
  - ✓ Over temperature
- 206 kbps throughput demonstrated in lab, over the air

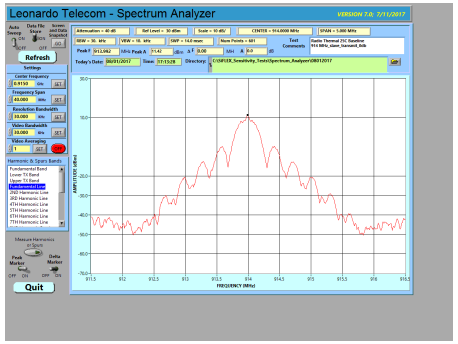
Field Test verified surface link properties



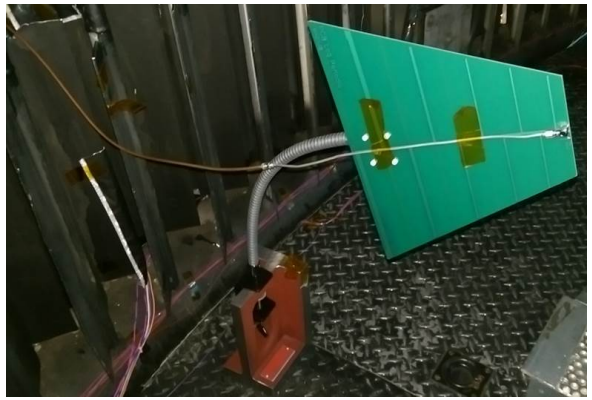


TCB and antenna on EDM-2 passed command and telemetry check

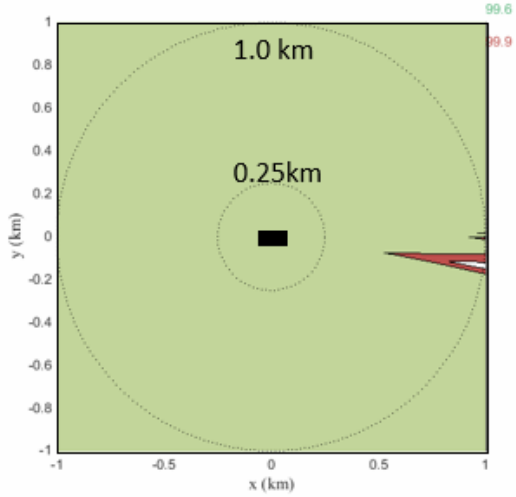
Threshold, interference, sortie, parameter measurements, flight assembly prep are ongoing



"Sniffer" antenna in chamber flight and ETL tests sees Helicopter EMI environment to support enhanced, more realistic performance testing

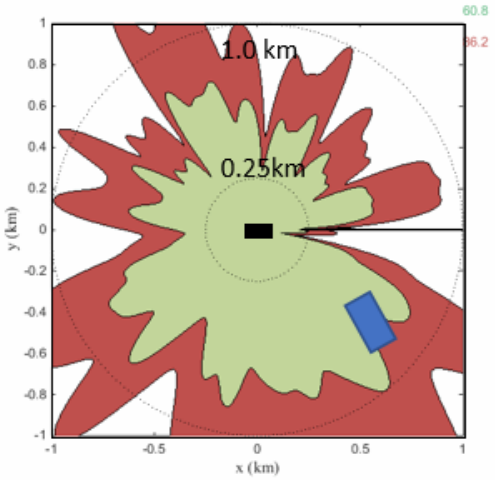


Telecom Analysis – Nacer Chahat

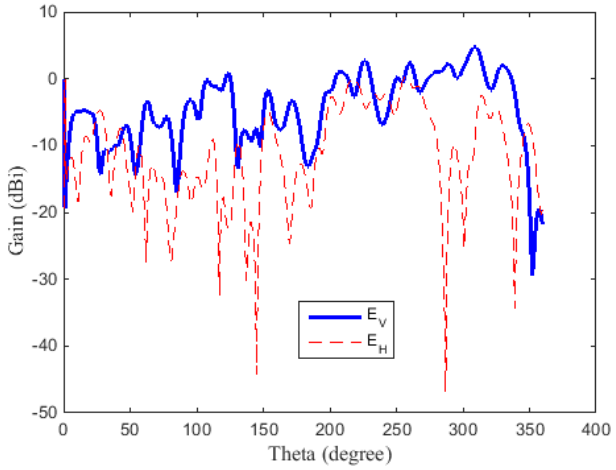


Predicted in-flight coverage

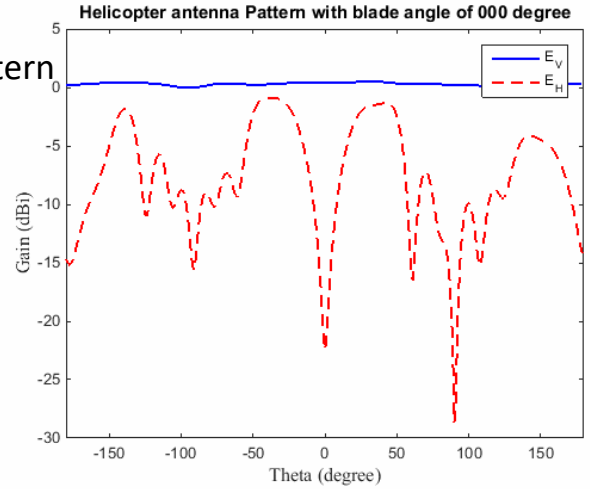
Green – high rate
Red – low rate
White – no coverage



Predicted landed coverage



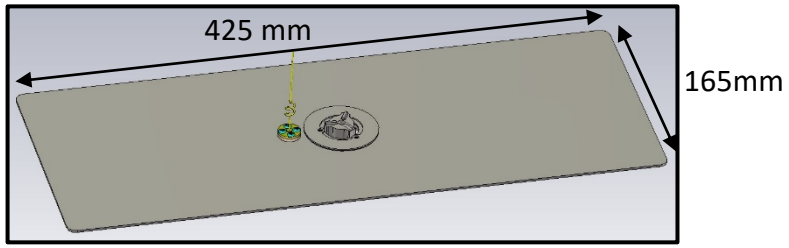
Rover Antenna Pattern



Helicopter Antenna Pattern

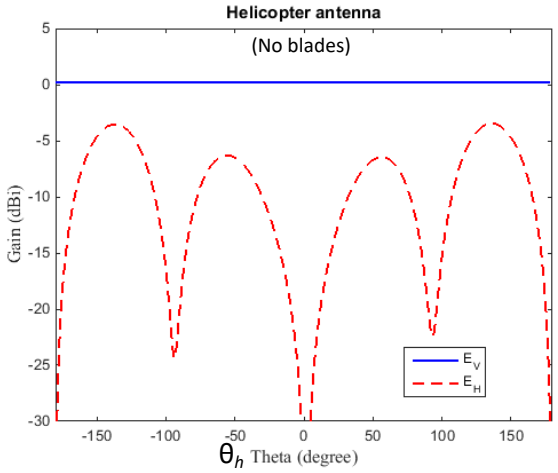
Helicopter antenna (rectangular solar panel)

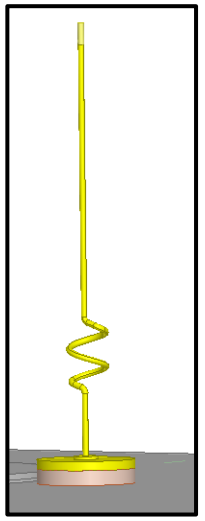
$H_{antenna}$ = 63mm



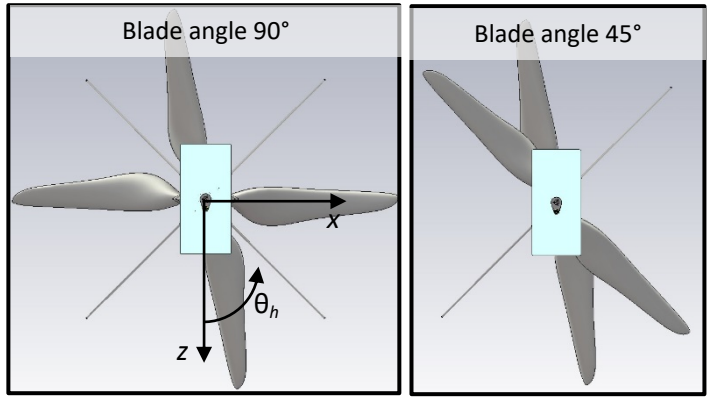
Helicopter antenna on its solar panel

HBA radiation pattern

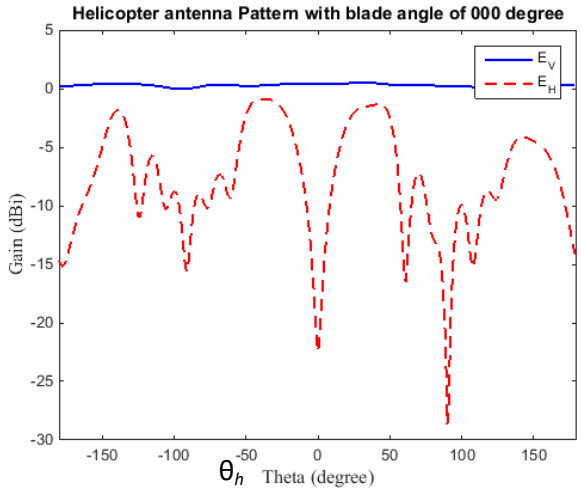




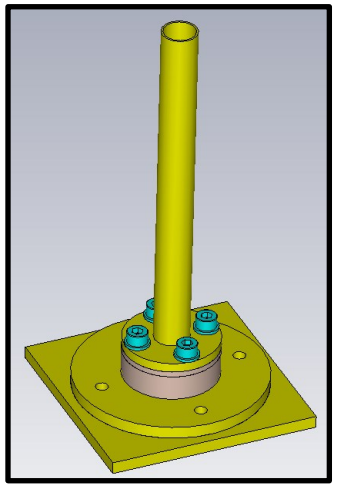
Antenna design



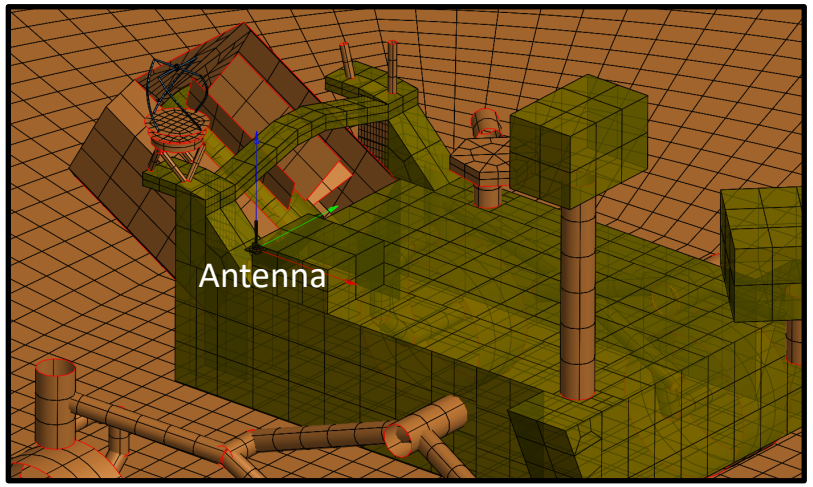
Helicopter antenna on its solar panel (includes blades)



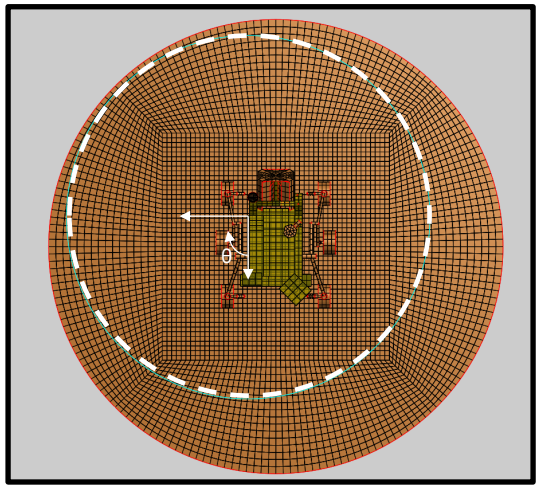
HBS Antenna performance on Mars2020 rover



Antenna design

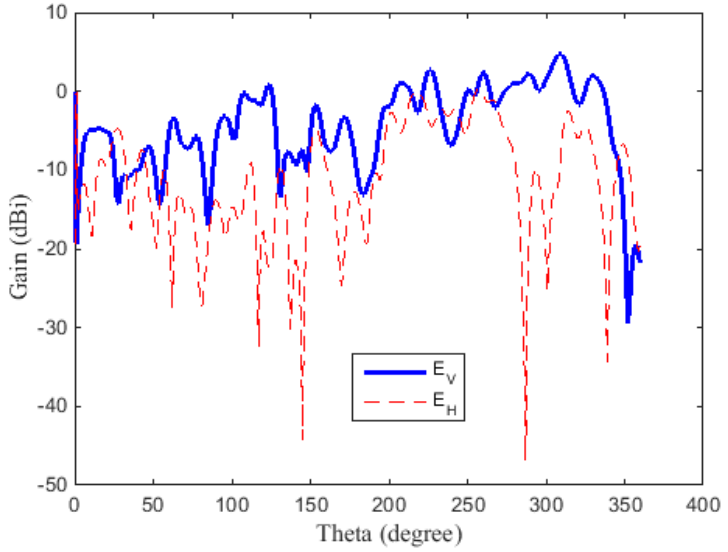


Antenna on M2020 Rover



Coordinate system

Helicopter Base Station Antenna (HBA) radiation pattern



Interpretation of results:

- Shadowing effects
- Multipath (reflections)
- Suffers from a very small ground plane
- Larger ground plane and/or location would improve the result

Map Coverage Around M2020 Rover on the ground: antenna 1

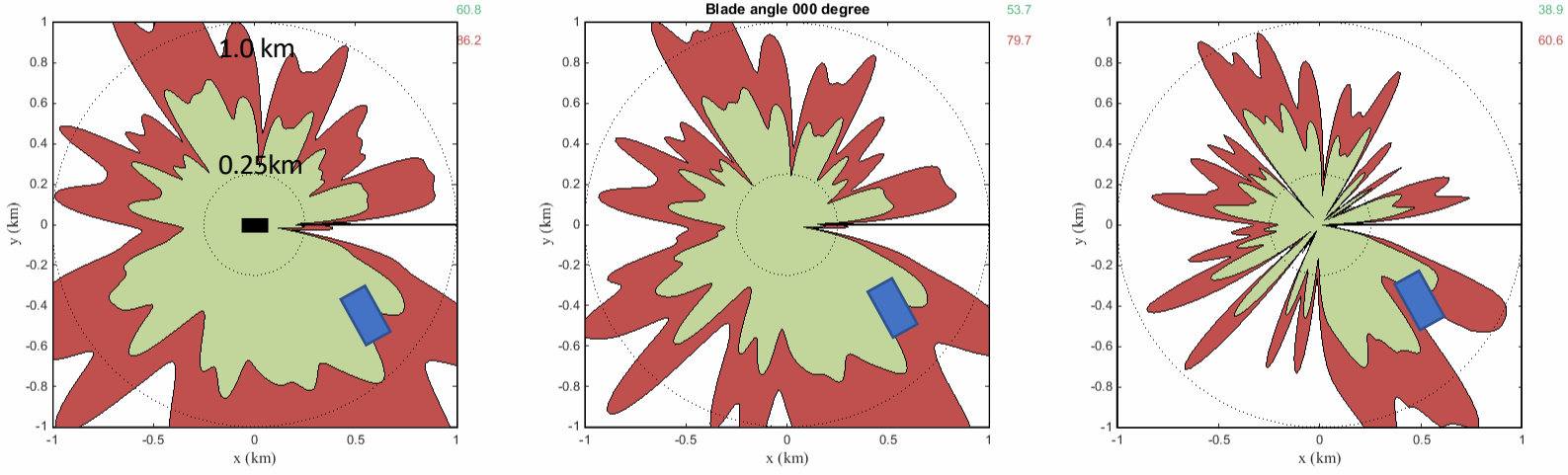
Map coverage assuming min, mean, max polarization loss with blade rotating.
The math is done for all azimuth angles around the helicopter.
These results were obtained using **Bullington** with h_t**=0.48m** and h_r=1.23m.

Received power of >-94dBm ⇔ 250kbps

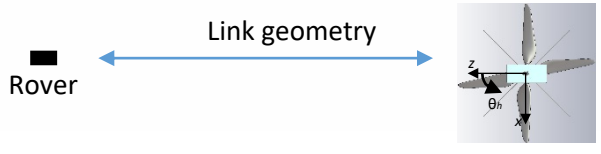
Received power of [-102, -94] dBm ⇔ 40kbps

No link

5%



Min polarization loss | Mean polarization loss | Max polarization loss



Azimuth angle θ_h = [0°-359°]

Map Coverage Around M2020 Rover with antenna 1 only: Flying

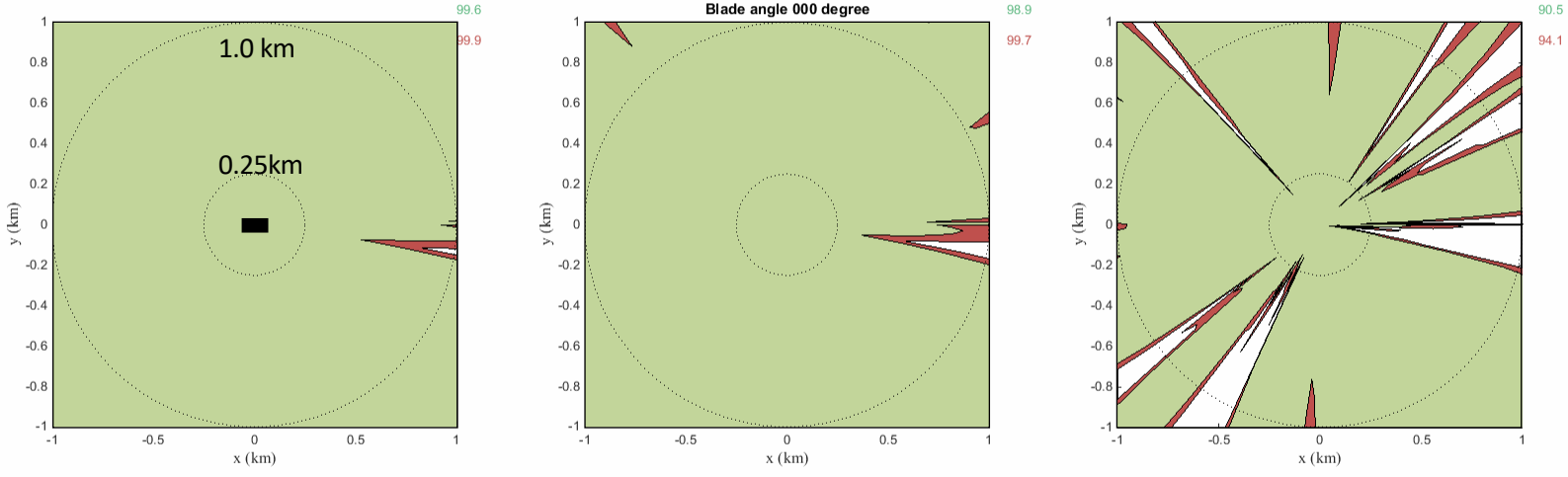
Map coverage assuming min, mean, max polarization loss with blade rotating.
The math is done for all azimuth angles around the helicopter.
These results were obtained using **Bullington** with $\boldsymbol{h_t}$**=10m**, h_r=1.23m, and Req = [0.25 - 1] km.

Received power of >-94dBm ⇔ 250kbps

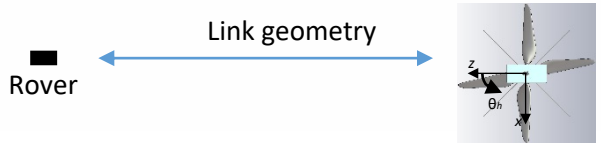
Received power of [-102, -94] dBm ⇔ 40kbps

No link

5%



Min polarization loss | Mean polarization loss | Max polarization loss



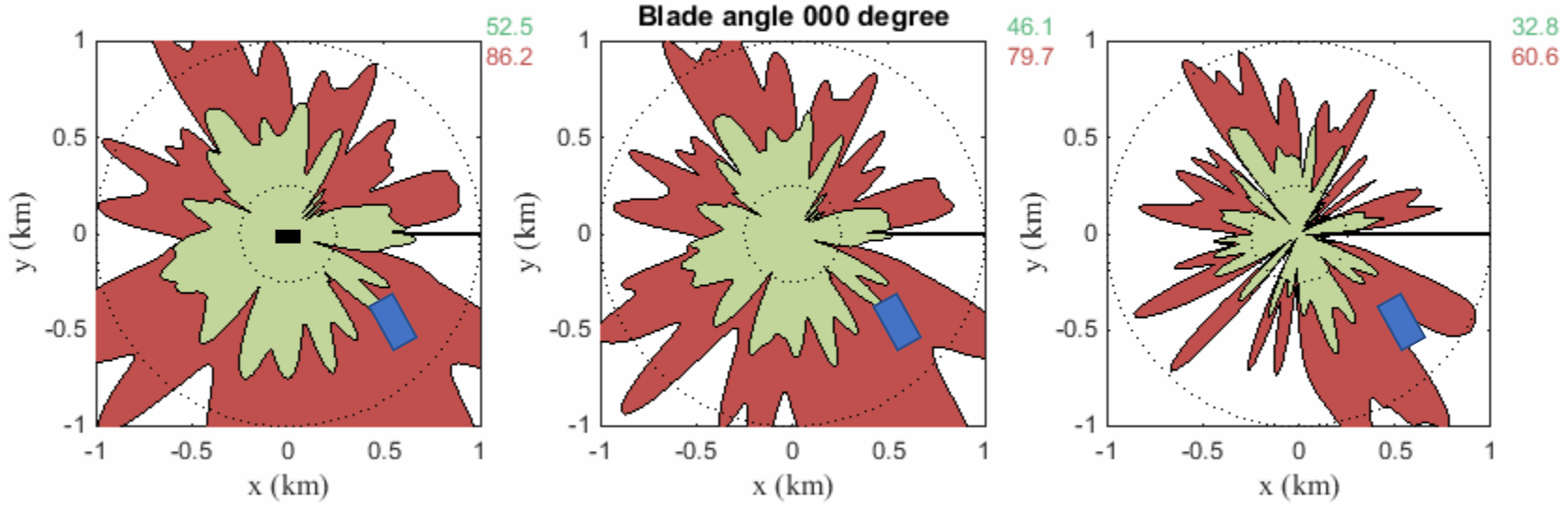
Azimuth angle θ_h = [0°-359°]

Map Coverage Around M2020 Rover on the ground: antenna 1

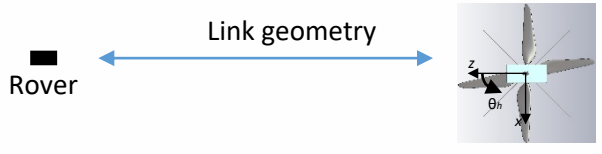
Map coverage assuming min, mean, max polarization loss with blade rotating.
The math is done for azimuth angle around the helicopter.
These results were obtained using **Bullington** with h_t**=0.48m** and h_r=1.23m.

Received power of >-94dBm ⇔ 250kbps (no margin) – 40kbps (8dB margin)

Received power of [-102, -94] dBm ⇔ 40kbps (no margin)



Min polarization loss | Mean polarization loss | Max polarization loss



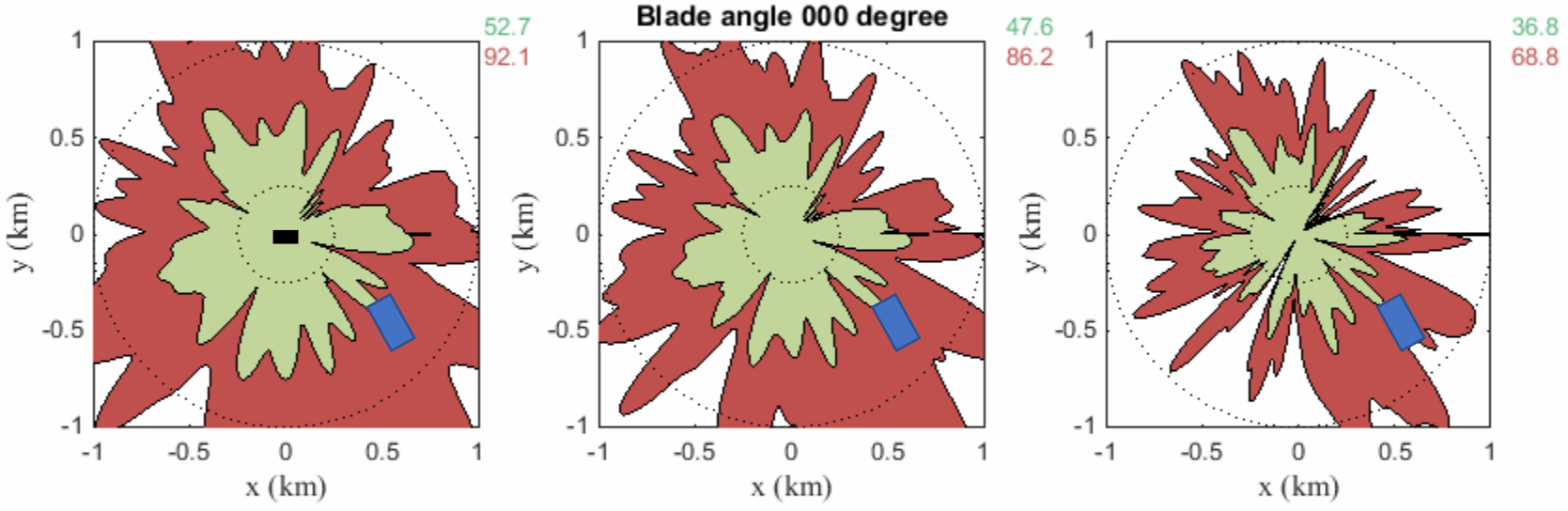
Azimuth angle θ_h = [0°-359°]

Map Coverage Around M2020 Rover on the ground: antenna 1 and 2

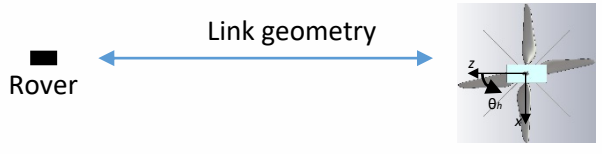
Map coverage assuming min, mean, max polarization loss with blade rotating.
The math is done for azimuth angle around the helicopter.
These results were obtained using **Bullington** with $\boldsymbol{h_t}$**=0.48m** and h_r=1.23m.

Received power of >-94dBm ⇔ 250kbps (no margin) – 40kbps (8dB margin)

Received power of [-102, -94] dBm ⇔ 40kbps (no margin)



Min polarization loss | Mean polarization loss | Max polarization loss



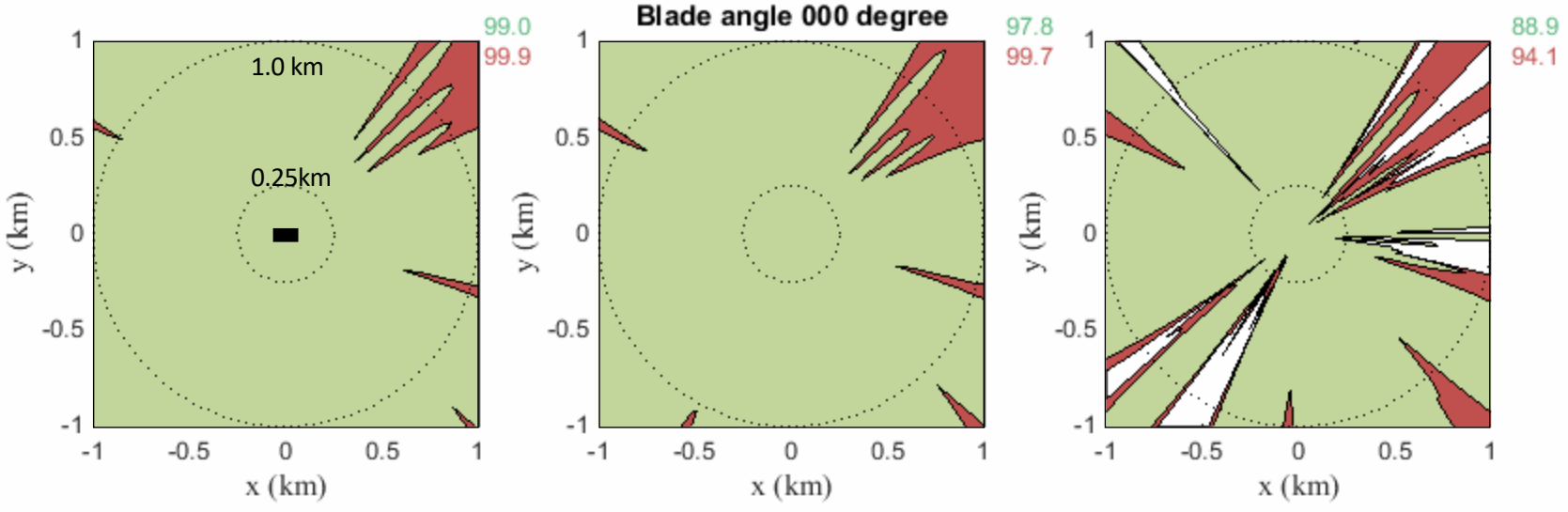
Azimuth angle θ_h = [0°-359°]

Map Coverage Around M2020 Rover with antenna 1 only: Flying

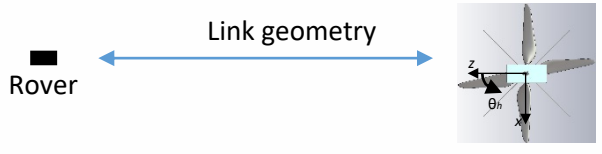
Map coverage assuming min, mean, max polarization loss with blade rotating.
The math is done for azimuth angle around the helicopter.
These results were obtained using **Bullington** with $\boldsymbol{h_t}$**=10m**, h_r=1.23m, and Req = [0.25 - 1] km.

Received power of >-94dBm ⇔ 250kbps (no margin) – 40kbps (8dB margin)

Received power of [-102, -94] dBm ⇔ 40kbps (no margin)



Min polarization loss | Mean polarization loss | Max polarization loss



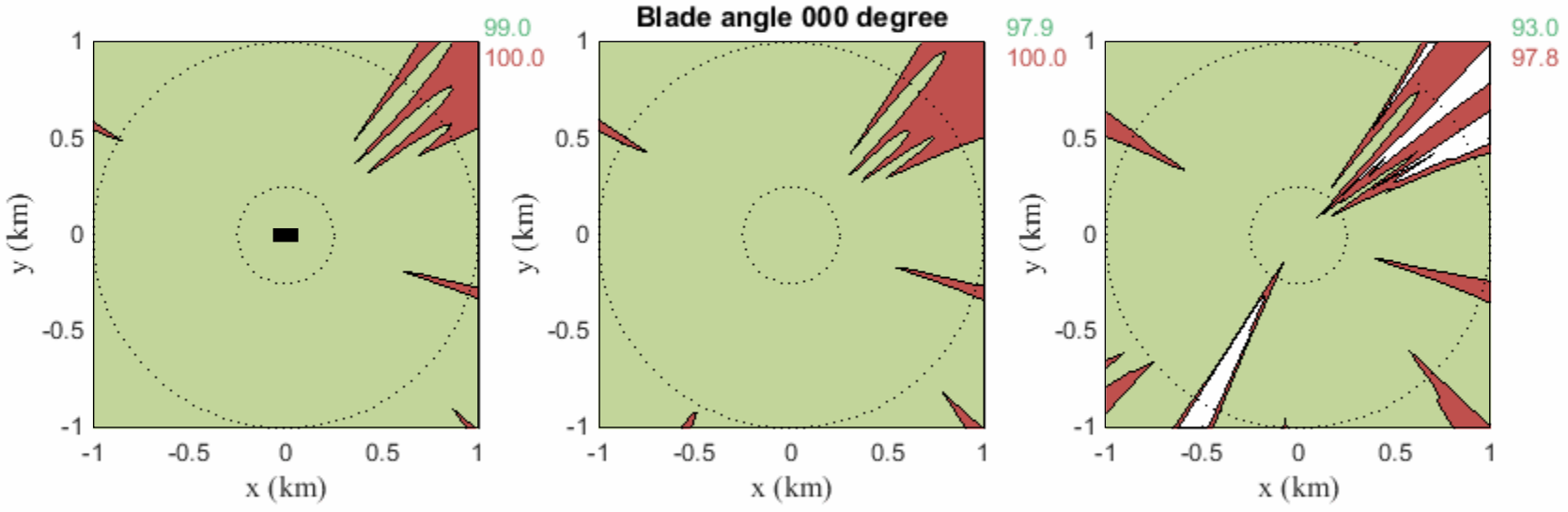
Azimuth angle θ_h = [0°-359°]

Map Coverage Around M2020 Rover with antenna 1 and 2: Flying

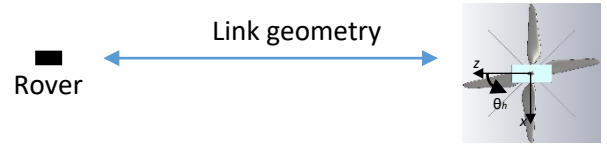
Map coverage assuming min, mean, max polarization loss with blade rotating.
The math is done for azimuth angle around the helicopter.
These results were obtained using **Bullington** with $\boldsymbol{h_t}$**=10m**, h_r=1.23m, and Req = 0.25m.

Received power of >-94dBm ⇔ 250kbps (no margin) – 40kbps (8dB margin)

Received power of [-102, -94] dBm ⇔ 40kbps (no margin)



Min polarization loss | Mean polarization loss | Max polarization loss



Azimuth angle θ_h = [0°-359°]

ConOps and SiFlex / Protocol Mods

- This is not a multimode mesh network (that ZigBee is meant for)
- This is a two-node network where radio silence needs to be enforceable from HBS, so
  - The helicopter speaks when spoken to via
- “Beacon Mode”
  - HBS beacons and helicopter replies in its slots, when powered
  - HBS silent, helicopter silent, regardless
  - Beacons assign slots to both sides for transmission

ConOps

- 250 kbps OTA down to -94 dBm
- 20 kbps OTA down to -105 dBm
  - 20 kbps not available in USA, but is on Mars ☺
- Actual throughputs are a fraction of the OTA rates, so

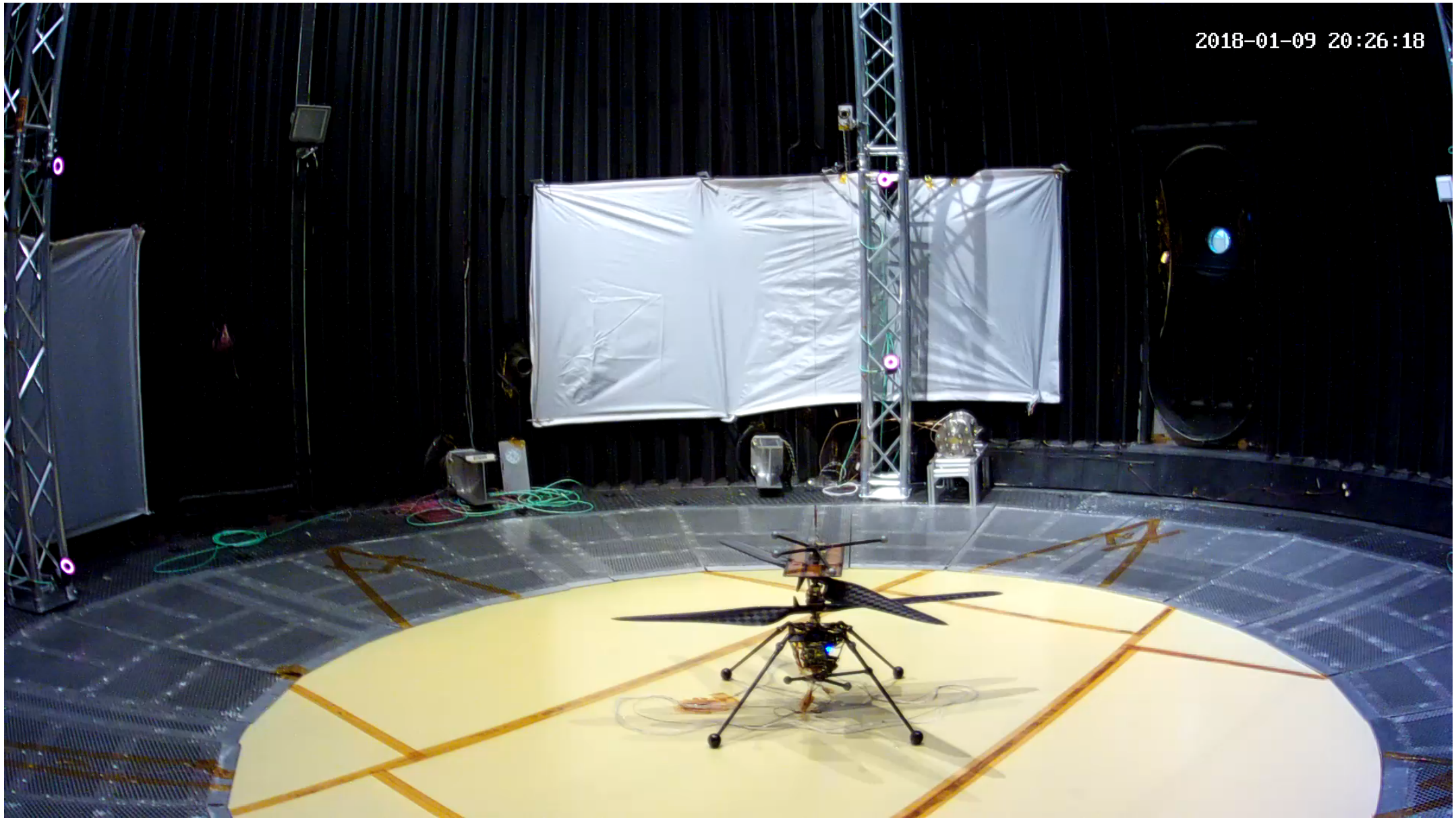
- Added *Vunerable One-Way InFlight MH Transmission* (VOMIT) mode to maximize throughput during aerial flight
  - Throughput approaches 200 kbps

Schedule?

- In June 2016 it was
  - EM by December 2016
  - Flight by June 2017
- In January 2018 it's
  - Fab flight boards now
  - FM Helicopter assembly starts April 1, 2018
  - HRCR September 2018
  - M2020 ATLO support TBD
- HBS work is coming along too
  - Same board to Telecom, but
- HBA and cables are a separate delivery to M2020, July 2018

Video of Hover Flight for the Record

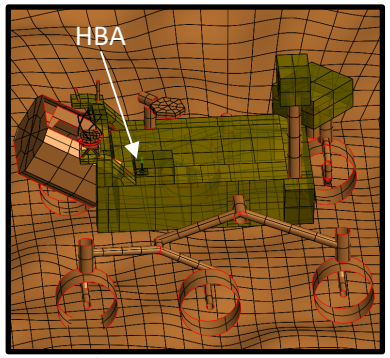
- Vicon targets (above and below) info comes back through WiFi
- On Mars this is done with onboard sensors (work to go)
- Telecom not used on these flights, but
- On Mars that’s all there is ☺
- The rest is autonomy


2018-01-09 20:26:18

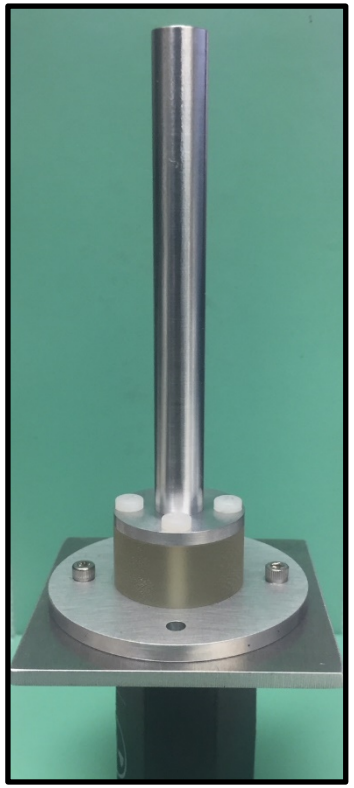
Questions?

Backup

Base Station Antenna



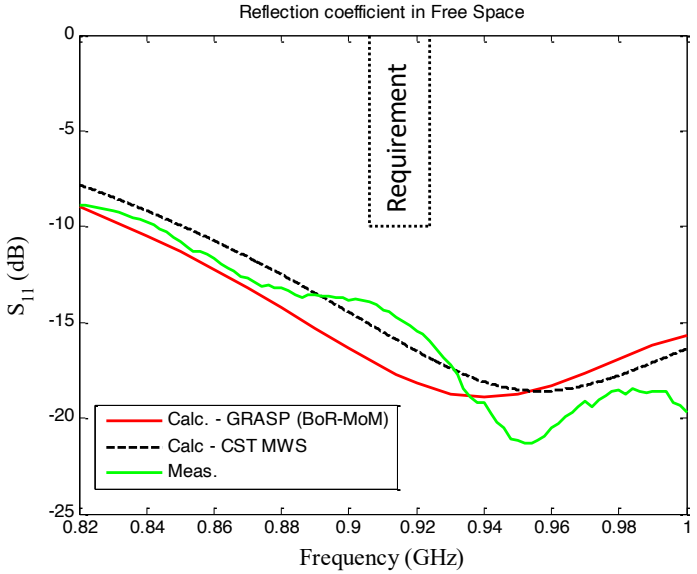
HBA: Helicopter Base Station Antenna

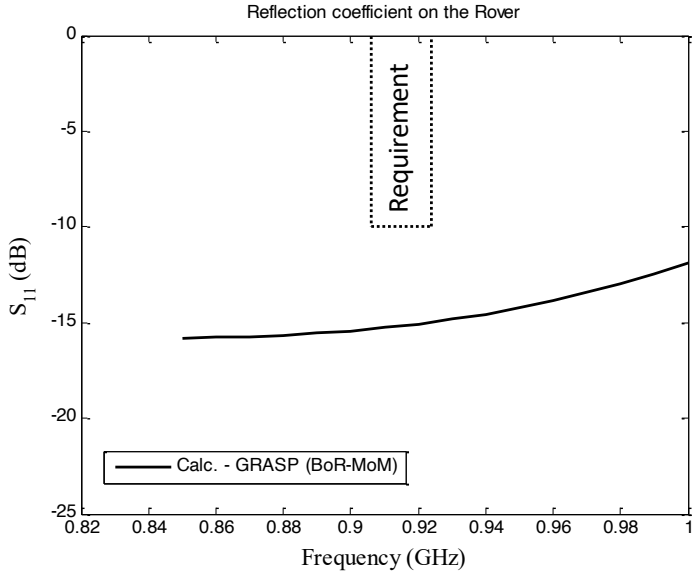


Helicopter Basestation Antenna (HBA) radiation pattern

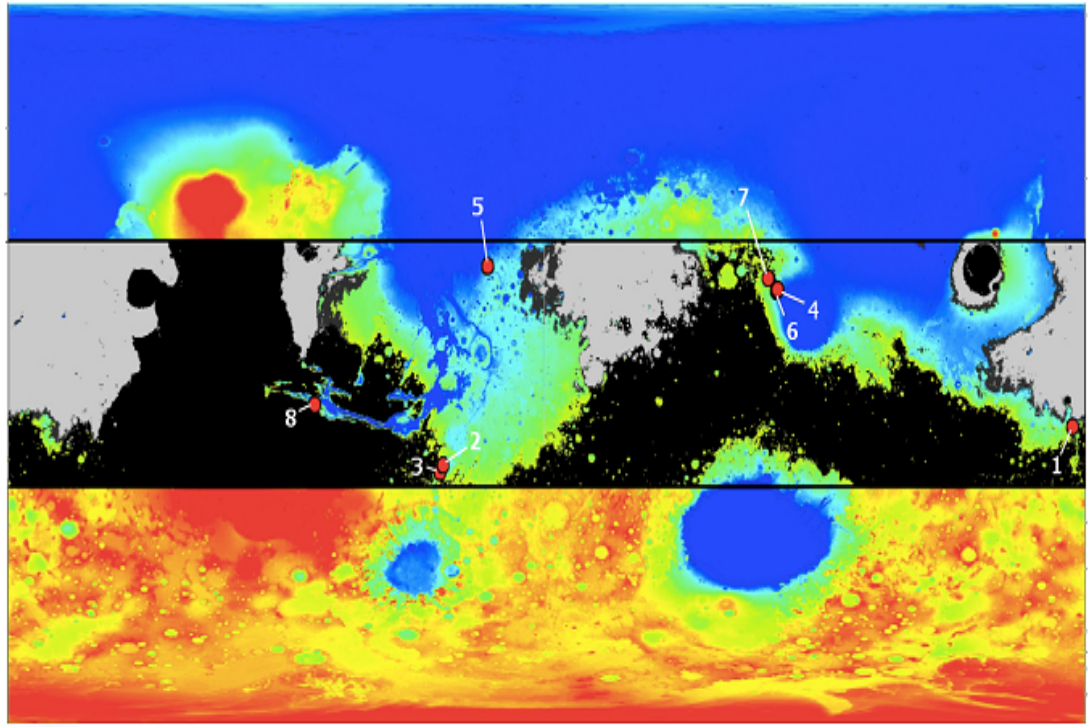
The HBA was designed and optimized on the Rover as the ground plane of the antenna is so small, it will impact the antenna performance. The reflection coefficient of the antenna should be lower than -10dB to minimize the amount of power reflected back to the radio (i.e. power loss and risk of damaging the radio).

The reflection coefficient of the HBA was fabricated and tested in free space. **Excellent agreement was obtained.** The antenna was simulated with two different tools. GRASP allows to simulate large structure such as the M2020 Rover with the Mars soil. This is not possible or too time consuming with other software such as HFSS and CST MWS. However, until now, complex antenna such as the HBA could not be simulated in GRASP. I managed to simulated it using BoR-MoM in GRASP allowing us to run quick simulation of the entire Rover with the antenna. The reflection coefficient was optimized on the Rover using GRASP.





The Current Mars Helicopter is Designed for Operation in the Northern-Hemisphere Landing Sites

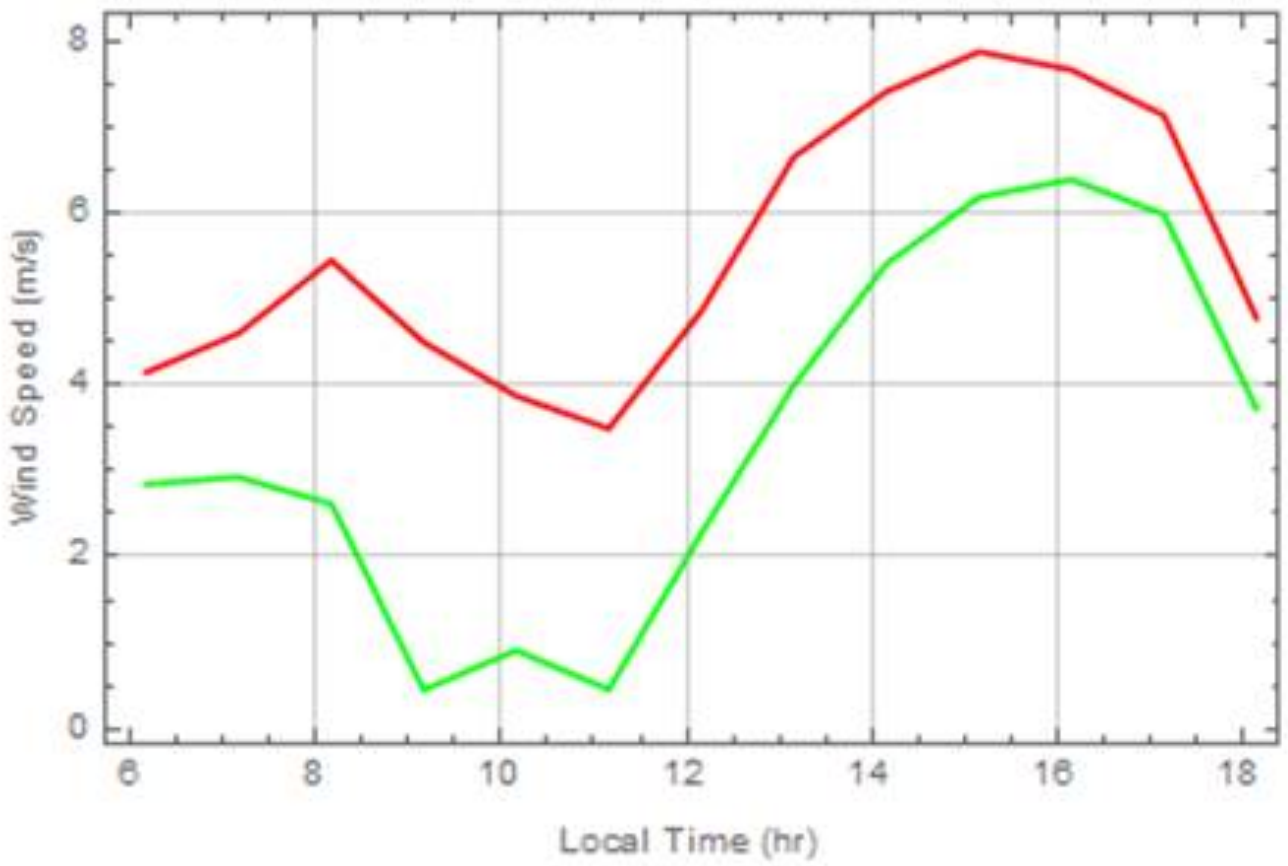


The 3 Candidate Landing Sites	Lat (deg N)	Long. (deg E)	Elev. MOLA (km)
1. Columbia Hills	-14.59	175.53	-1.89
4. Jezero	18.39	77.54	-2.62
6. NE Syrtis	17.89	77.16	-2.03

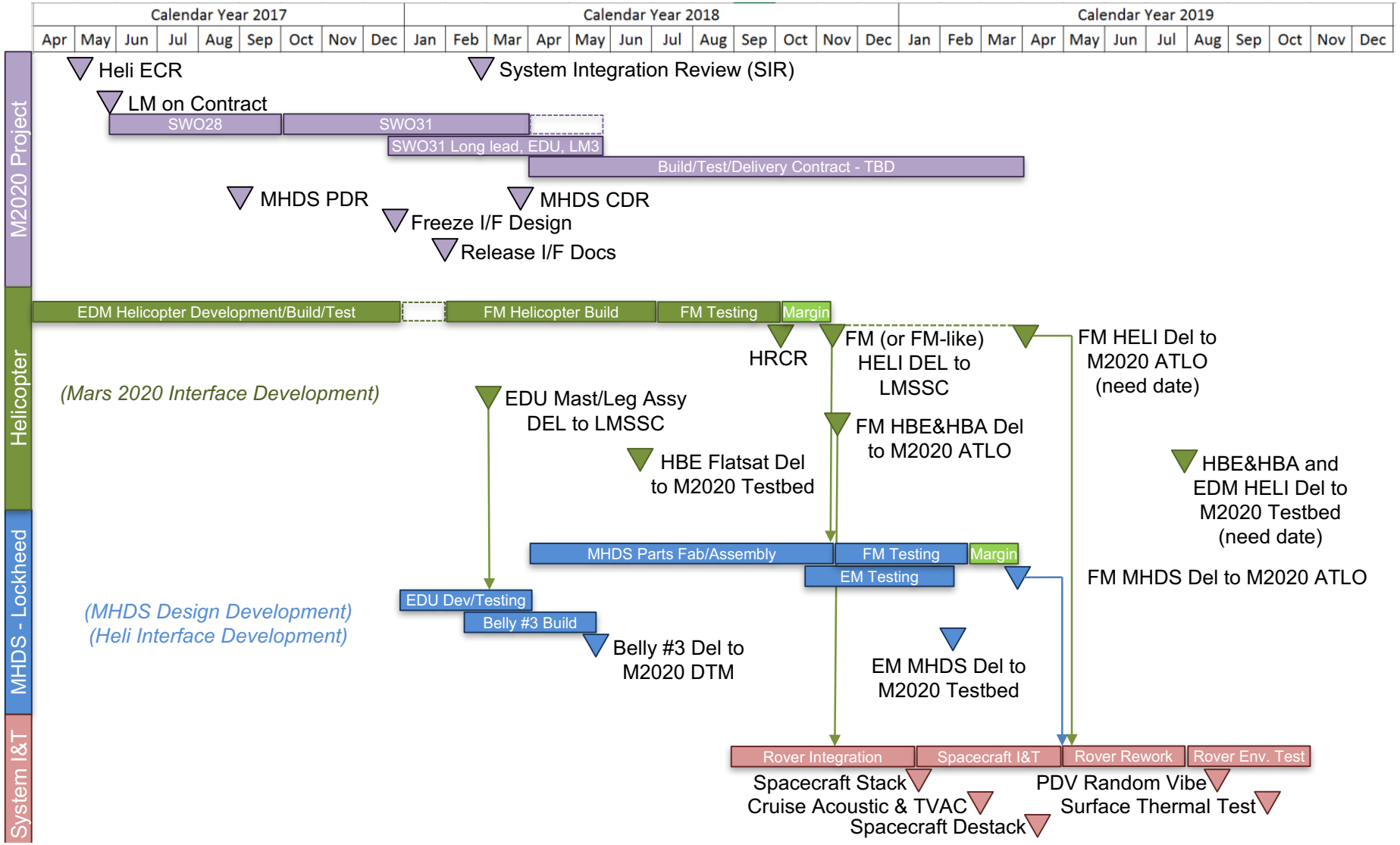
- In EDM phase, learned that major percentage of available energy on the helicopter is needed for heaters to survive through cold temperatures
- A single helicopter design cannot close for both Northern and Southern hemispheres
    - In 2021, the northern sites will be in Spring-Summer phase and southern sites will be in Fall-Winter phase
- Focused EDM Mars Helicopter design to close for the Northern site
    - Thermal survival in the Fall-Winter will require more Energy and Thermal Insulation – not in scope of work - additional design changes will be required with additional time/$

43

Ground Winds at Solar Panel Height



Mars Helicopter Interface Activities with M2020

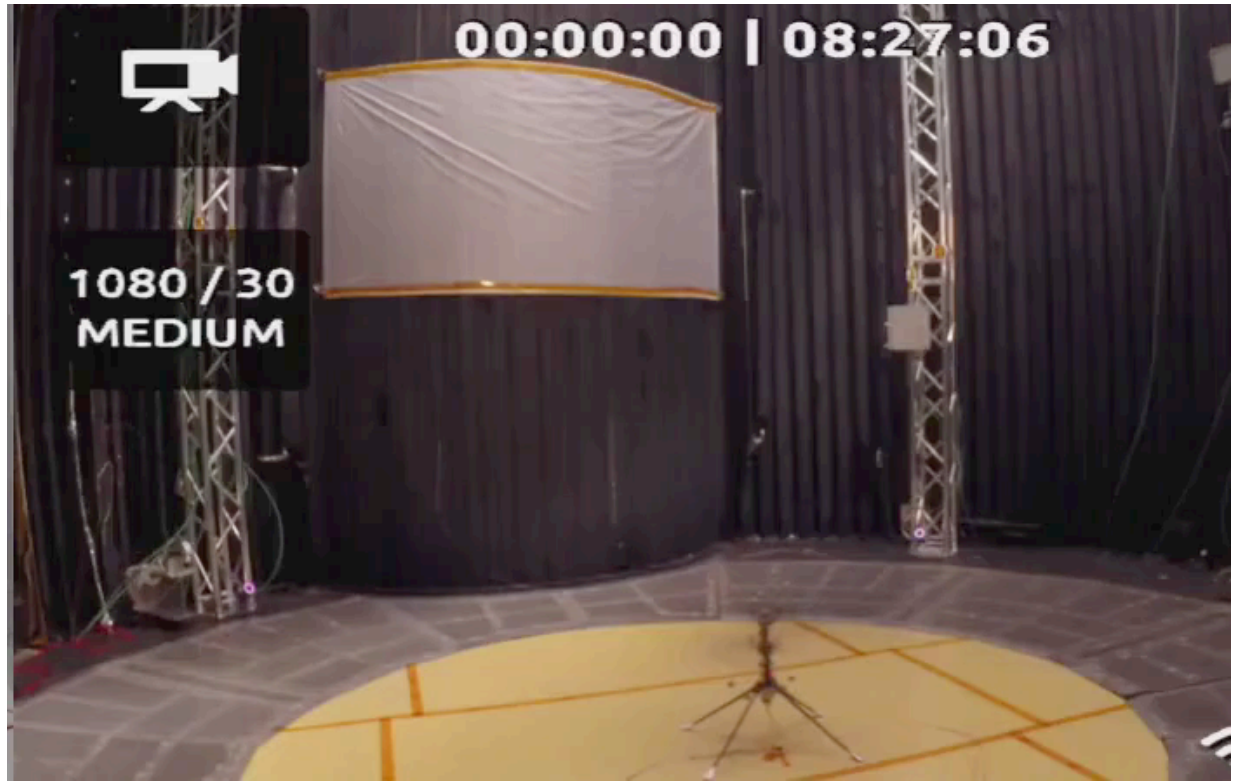


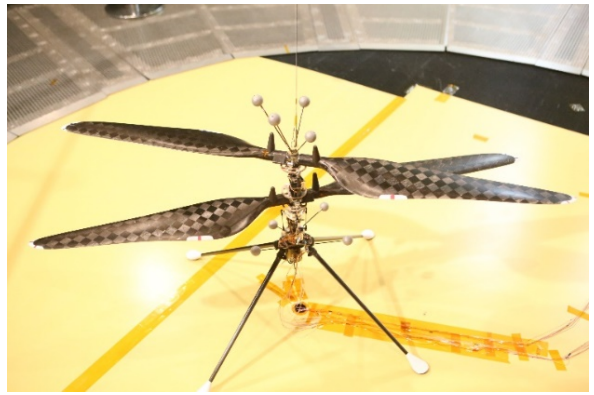
Demonstrated Feasibility of Fight at Mars (5/31/16)

- Full-sized prototype rotor system and autonomous flight control
  - Flight Computer (PC) and Power System (shore power) were tethered from ground

- JPL 25’ Space Simulator chamber, vacuum backfilled with CO_2 to Mars atmospheric density (0.0175 kg/m^3; ~1% of Earth)

- Demonstrated autonomous, closed-loop, controlled flight under Mars-like conditions

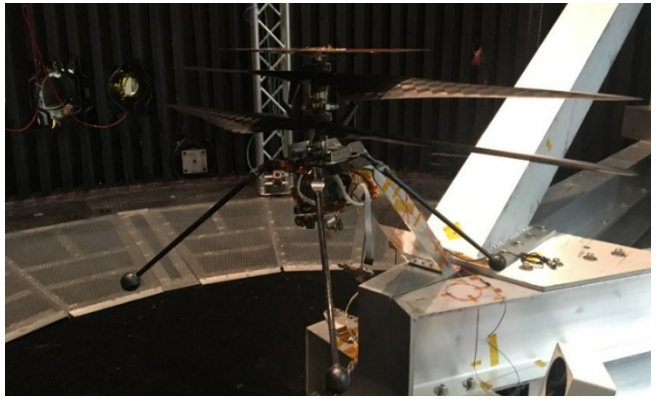




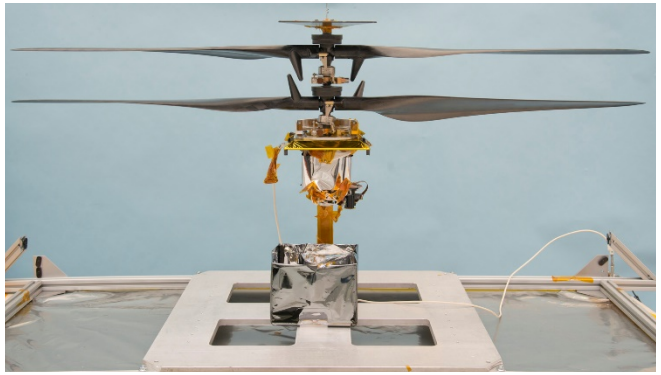
Engineering Design Model Vehicles Met the Stringent Constraints for Mars

- **Mass** Met requirement for Mars flight
  - As-built: 1.78 Kg
- **Volume** compatible with Rover accommodation
- **Helicopter aerodynamic/power/energy** performance met
- **Original Mars Helicopter architecture held – no changes needed for FM**
  - Rotor System – Integrated Avionics – Power - Telecom - Thermal – Motor Control - Flight Control
- **Thrust and stable flight control**
  - Validated simulation for hover flight
  - Simulations extended successfully to forward flight with winds

    up to 9 m/s
  - Flight tests to-date match modeling & simulation

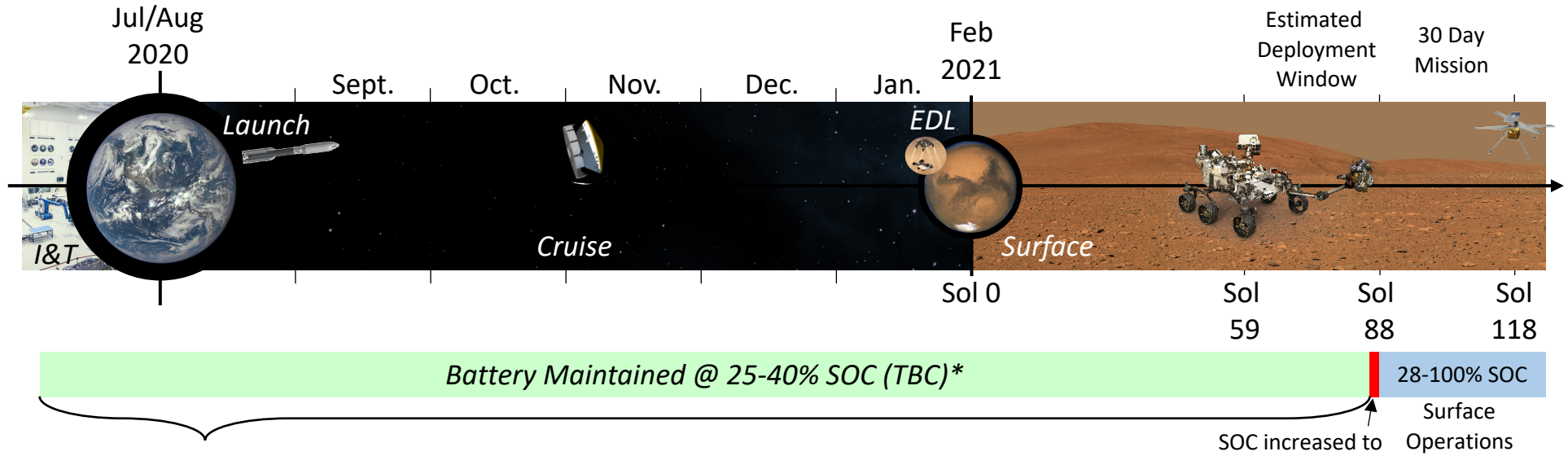


EDM-1 Helicopter



EDM-2 Helicopter

Mission Profile



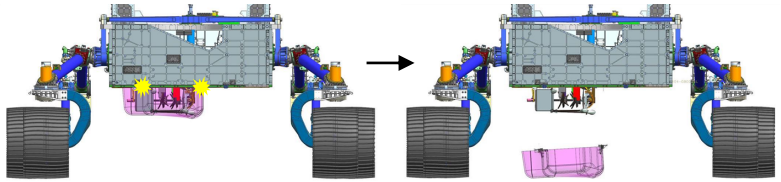
- Helicopter in hibernate except during periodic charging
  - < 15mW (TBC) parasitic loss during hibernate
    - Discharges battery 15% in 18 days
  - Allows recharge once every two weeks (TBC)
  - ~40 minutes to increase battery SOC 15% @ 0.5A
- Independent survival heaters maintain helicopter (batteries) within AFT (0-25°C) during cruise
- Battery state of health monitored via:
  - Base Station: V_{BATT}, I_{HBS}, T_{BATT} (2 of each)
  - Helicopter: V_{BATT}, V_{CELLS}, I_{ECM}, I_{SA}, I_{MOTOR}, T_{BATT}

Base Station PEL

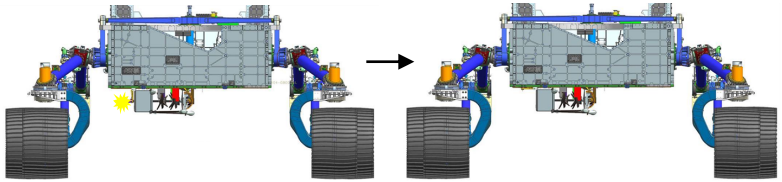
	Stowed Hibernate	Stowed SOH	Stowed SOH/CHRG	Deployed Sleep	Deployed Rcv.	Deployed Tx.
Helicopter	0.015	0.334	0.334	0.000	0.000	0.000
Batt. Charge	0.000	0.000	12.775	0.000	0.000	0.000
HBS Pwr+Harn	0.026	7.095	23.126	0.000	7.881	12.332
HBS Thermal	1.268	1.268	1.268	0.000	0.000	0.000
HBS Avionics	0.000	4.546	4.546	0.000	4.546	10.561
HBS Telecom	0.000	0.000	0.000	0.000	2.145	3.250
Total (W)	1.308	13.242	42.048	0.000	14.572	26.144

Helicopter Deployment Overview

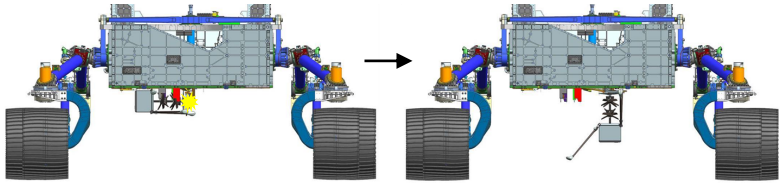
A: Jettison Debris Shield
¼" Cable Cutter Pyros fired severing restraint cables that allows the Debris Shield to drop from the Rover. After drop Rover executes forward drive to prepare for rest of deployment activities



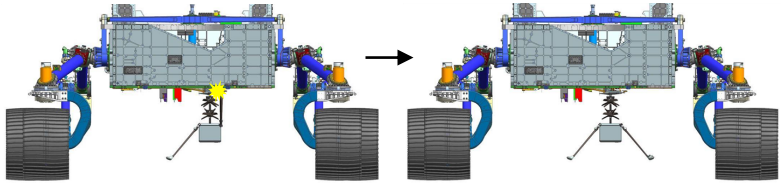
B: Heli Launch Lock Release
Frangibolt energized releasing lower Heli Launch Lock Restraint. Egress Arm / Heli Assy held in place by Egress Arm Restraint



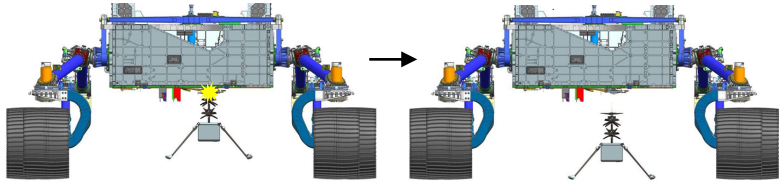
C: Egress Arm Restraint Release and Egress Arm Deploy
Cable Cutter Pyro fired releasing MHDS Egress Arm. Egress Arm Release initiates rotation of Egress Arm & Heli with actuator in dynamic braking mode. Near the end of the deploy motion the actuator completes the arm deploy motion by driving to the hardstop and latching.



D: Leg Restraint Release
Cable Cutter Pyro fired releasing Helicopter Leading Legs allowing them to spring into their fully deployed state. Helicopter is fully configured for drop after this event.



E: Primary Heli Restraint Release & Heli Drop
Frangibolt energized releasing Helicopter from Rover & Egress Assy. Helicopter drops to Martian Surface below Rover. After nominal drop is confirmed via telemetry and imagery review Rover executes forward drive to allow Heli Solar Arrays to resume charging

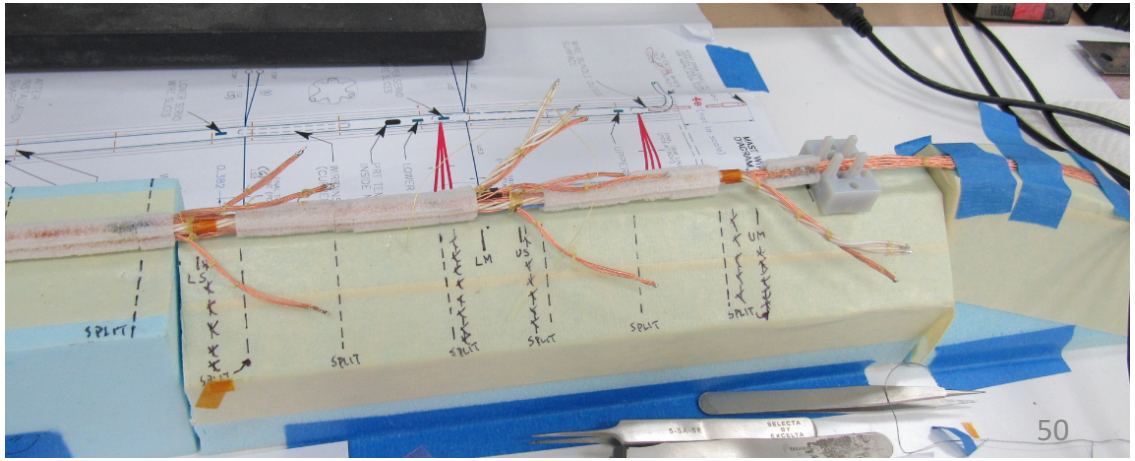


Antenna Location, Mast Bundle

- On top because most comm is from the ground
- And 10 m. altitude / 250 m range is 4 milliradians elevation

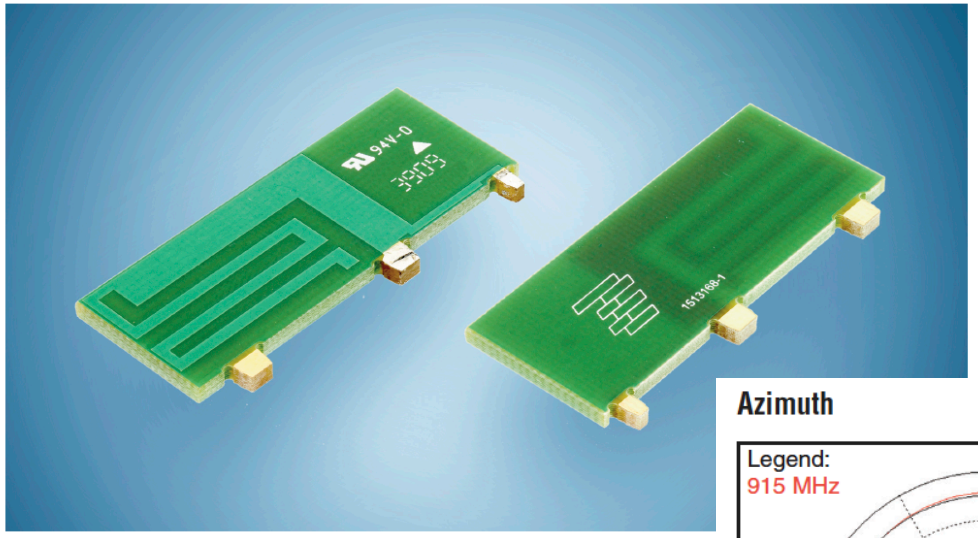
- Heli antenna on top of solar panel (ground plane)
  - Cable routed through mast during mast assembly
  - GPPIO on antenna side
  - Soldered to SiFlex in final assembly on radio side

- Helicopter Base Antenna (HBA)
  - Delivered directly to M2020
  - Flight cables



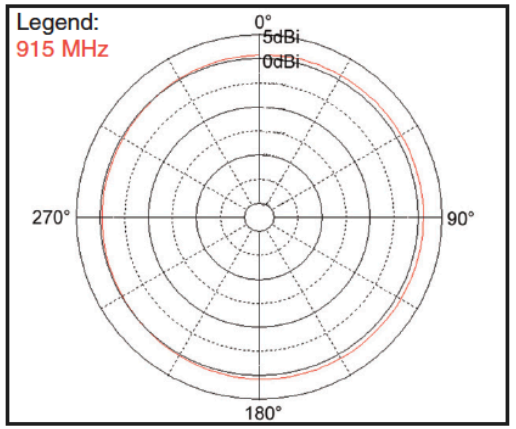
Original
Helicopter Side Antenna
Tyco Electronics

902 – 928 MHz – Single Band Antenna (includes frequencies of 915 ISM and ZigBee US)

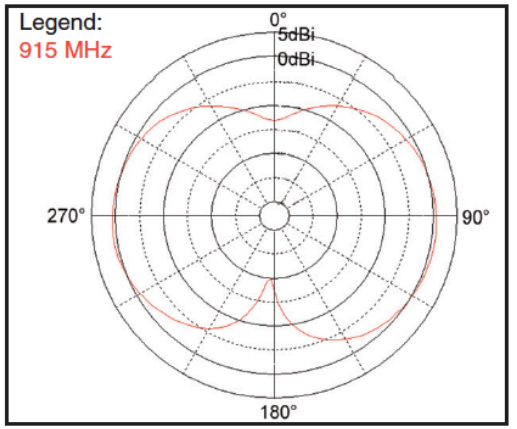


Length: 38 mm
Height: 15 mm
Mass: 1.8 grams (Measured)
Gain: ~0 dBi
Polarization: Vertical
PCB Solder attachment

Azimuth



Elevation



Free Space Radiation Patterns

MH Telecom Risks

- COTS
- ATLO support – testing
- Protocol (retired)
- Link performance
- One iteration
- Antenna placement